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COATINGS FOR LIGHTNING PROTECTION OF STRUCTURAL REINFORCED PLASTICS

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TECHNICAL REPORT AFML-TR-70-303 PART II

Air Force Materials Laboratory
Nonmetallic Materials Division
Air Force System Command
Wright-Patterson Air Force Base, Ohio

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COATINGS FOR LIGHTNING PROTECTION OF STRUCTURAL REINFORCED PLASTICS

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FOREWORD

This report describes work accomplished under contract F33615-71-C-1198, "Development of Coatings for the Lightning Protection of Structural Reinforced Plastics." This contract was administered under the direction of the Elastomers and Coatings Branch, Nonmetallic Materials Division of the Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio. Mr. James H. Weaver was the project monitor. This effort was a continuation of research initiated under contract F33615-69-C-1512, "Coatings for the Lightning Protection of Structural Reinforced Plastics."

The program was performed by the Electrodynamics Technology and the Structures Technology—Materials organizations of the Commercial Airplane Group The Boeing Company. Key personnel associated with the program and their respective areas of responsibility were:

R. W. Sutton	Program manager
R. O. Brick	Technical leader
C. H. King	Electrodynamics
J. T. Quinlivan	Materials

This report was submitted by the authors on January 17 1972.

This report has been reviewed and is approved.

W. P. JOHNSON, Chief
Elastomers and Coatings Branch
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ABSTRACT

Coatings and coating systems developed for protecting boron-filament- and graphite-fiber-reinforced plastic composites from structural damage by lightning strikes were investigated and developed. These coatings are 6-mil-thick aluminum foil, 200 by 200 mesh aluminum wire fabric, 120 by 120 mesh aluminum wire fabric, and a coating containing aluminized glass filaments. These coatings all use a continuous-metal member as the protective element (e.g., metal foil, woven wire fabric, or metallized glass filaments). Each of these was found capable of preventing mechanical damage to the composite at the 100-kA test level. Very local and minor damage was frequently, but not always, detected after 200-kA testing. None of the coatings could fully protect the composites from damage due to the high-coulomb component of the artificial lightning stroke.

With but one exception, the coatings investigated were relatively unaffected by normal aircraft environments. Their electrodynamic properties were measured and assessed.

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1.0 INTRODUCTION

Boron-filament- and graphite-fiber-reinforced plastics present new problems to the design engineer concerned with lightning protection. Techniques employed to protect conventional aluminum aircraft and their dielectric components are not directly applicable to advanced composite structures. The conductive, tungsten-rich core of the boron filament and the inherent conductivity of the graphite fiber render their reinforced plastics dielectrically inhomogeneous. As a result, these plastics require some form of lightning protection.

Investigations under contract F33615-69-C-1612 resulted in development of several exterior surface coatings that can prevent catastrophic lightning damage to advanced composites (Ref. 1). The most efficient (i.e., minimum weight) coatings use a metal wire fabric as the current-conducting member. Other coating systems investigated include metal foils, sprayed aluminum, and conductive paints. Lightning protection can also be provided by surface coatings that have very high dielectric breakdown strengths. Such coatings require appropriately spaced metal bars or strips to divert the electrical currents.

The effective use of any of these coatings requires an awareness of their impact on all aircraft systems to ensure that economy and operational performance are not compromised. To achieve this end, an Air Force Materials Laboratory program was instituted to develop and further study effective lightning protection coatings. The goals of this program were:

- Develop successful coating systems of optimum weight, cost, repairability, and manufacturing ease
- Investigate the effects of a wide range of adverse environments on the lightning-protective qualities of the coatings and develop the necessary modifications to improve coating performance
- Investigate the electrodynamic properties of the coatings and assess their impact on aircraft systems operation
- Investigate new coating concepts that will reduce the weight or cost of satisfactory protective coatings

To implement these objectives, selected coating systems were applied to boron-filament-and/or graphite-fiber-reinforced epoxy laminates. The electrical parameters of the coating were measured; the coated panels were exposed to the required adverse environments (if any) and subjected to artificial lightning discharges. The performance of the coating system was determined by visual damage analysis, microscopy, and the residual mechanical properties of the composite. Successful coating systems were subjected to lightning restrikes to provide additional data and greater confidence levels for the coating systems.

2.0 COATING DEVELOPMENT

2.1 REINFORCED PLASTIC SUBSTRATES

2.1.1 Filament and Fiber Reinforcement

The boron filaments were manufactured by the Hamilton Standard Division of United Aircraft Corporation, Windsor Locks, Connecticut. The filaments were impregnated with a high-temperature epoxy resin by the Minnesota Mining and Manufacturing Co., St. Paul, Minnesota, and marketed under the designation "Scotchply" SP-272. Two forms of impregnated tape were used; one employed a style 104 glass scrim carrier, the other did not.

The graphite fibers were manufactured by the Union Carbide Corporation, New York, New York. The Thornel 50S graphite yarn was impregnated with WRD 1004, an epoxy resin, by the Research and Development Division, Whittaker Corporation, San Diego, California. Thornel 50 fibers were impregnated with BP 907 epoxy resin (American Cyanamid Corporation, Wallingford, Connecticut) by the Chemstrand Research Center, Durham, North Carolina.

Epoxy-resin-impregnated style 181 E-glass fabric was used as the control material. This material, Narmco 551-181, was manufactured by the Narmco Materials Division, Whittaker Corporation, Costa Mesa, California.

2.1.2 Test Panels

The test panels varied in size from 6- by 12-in. to 12- by 12-in.

The boron-filament- and graphite-fiber-reinforced laminates consisted of several plies in an alternating 0°-90° orientation. The boron-filament-reinforced laminates were constructed symmetrically about the center ply, with the glass carrier fabric (if any) providing the outer surfaces. Generally, the laminates were five plies thick. A few 14-ply laminates were prepared for special testing, e.g., electromagnetic shielding determinations and the joint Boeing-McDonnell Douglas lightning test.

The glass-fabric-reinforced control panels were constructed of 13 plies of style 181 E-glass fabric.

Unidirectional and bidirectional laminates were specially fabricated for control tensile test data. The specimen drawing is shown in Figure 1. The unidirectional laminates were seven plies and the bidirectional laminates were five plies. The doublers were prepared from four plies of Narmco 551-181 and were bonded to laminates using an oven cure (90 min at 260° F) under vacuum bag pressure. Surface preparation of the laminate included scouring with Scotch-brite followed by an MEK wipe.

The laminate plate with the four bonded doubler strips is cut into 1/2-in.-wide specimens using a diamond cutoff wheel and surface grinding techniques. An earlier specimen design using a 9-in.-long test specimen was discarded as it was not representative of the 12-in.-long lightning test specimens.

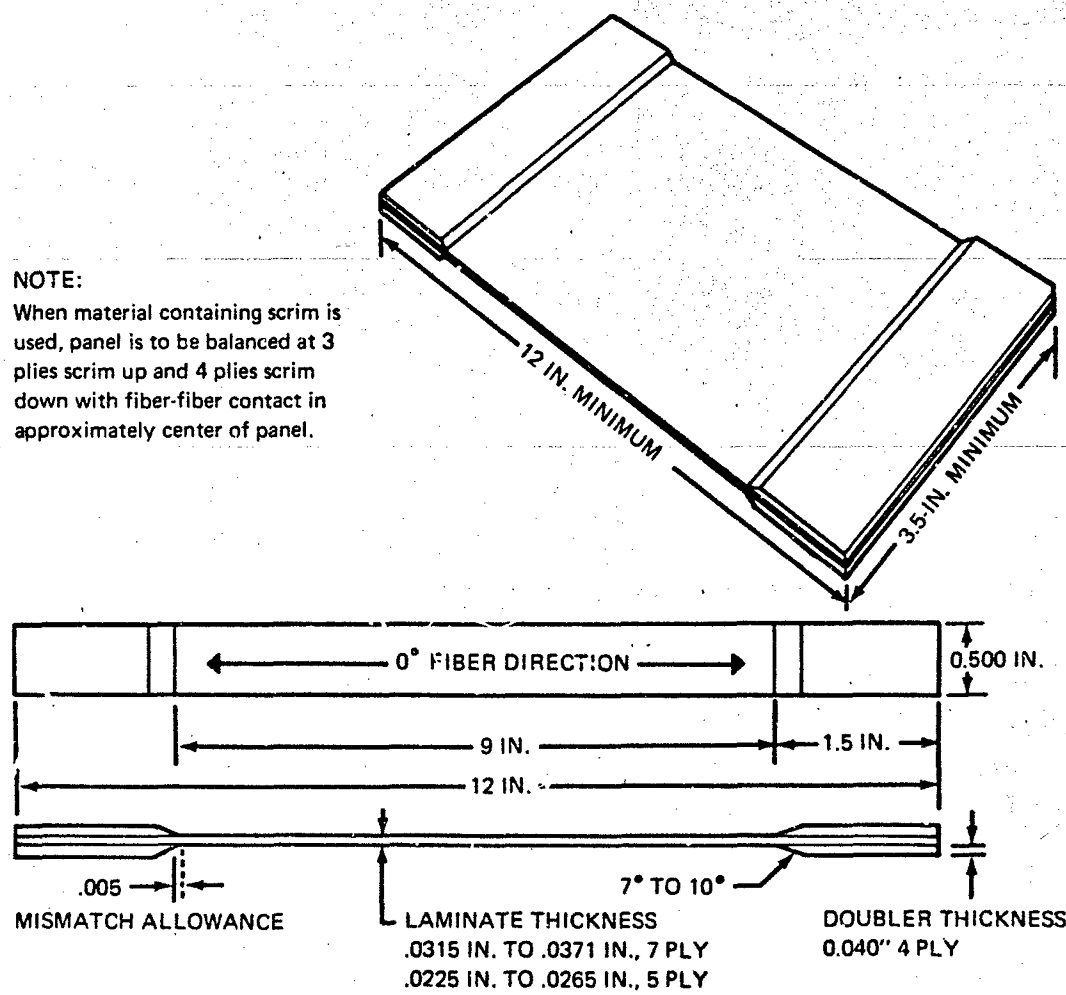


Figure 1. Tensile Test Specimen

The boron-filament-reinforced and Thornel 50-fiber-reinforced composites were autoclave cured per Boeing material specification (BMS) 8-131G (Ref. 2). This schedule requires 30 min at 180° to 190° F and at 280° to 290° F, followed by a 1-hr cure at 350° to 360° F, all under full vacuum and 50 psi pressure. The part is heated at 3° to 12° F/min and cooled at -3° to -5° F/min. No postcure is required.

The Thornel 50S/1004 high-modulus composites were cured per instructions provided by Whittaker. The schedule includes heating at 3° F/min to 275° F and holding at this temperature for 30 min. Upon completion of the hold period, 75 psi is applied, the vacuum bag is vented, and the part is heated at 6° F/min to 350° F. The part is held at this temperature for 150 min. The parts were cooled at -3° F/min under pressure.

The glass fabric control panels were cured per BMS 8-79K (Ref. 3), i.e., 90 min at 250° F under 50 psi, vented.

2.2 COATINGS

2.2.1 Metal Foils

Aluminum foil 1 and 6 mils thick was obtained from the Alcoa Company, Pittsburgh, Pennsylvania. The foil was integrally bonded to the outer surface of the composite.

A two-ply foil coating was prepared by perforating the aluminum. The perforations were approximately 1/16 in. in diameter and spaced 1/4 in. apart. A single ply of 104 glass scrim cloth impregnated with BP 907 was sandwiched between the pieces of aluminum and the assembly was integrally bonded to the laminate.

2.2.2 Wire Fabrics

Woven wire fabric was purchased from Pacific Wire Products Company, Seattle, Washington. The pertinent fabric parameters are as follows:

Fabric	Mesh Density	Wire Diameter (in.)
Aluminum	60 x 60	0.008
Aluminum	120 x 120	0.004
Aluminum	200 x 200	0.0021
Copper	100 x 100	0.0045

These fabrics were integrally bonded to the composite substrates during laminate manufacture.

It was necessary to add resin to the laminates to ensure proper resin flow and encapsulation of the fabric. This was accomplished either by impregnating the fabric with BP 907 laminating dispersion or by adding sufficient unsupported BP 907 adhesive film. Additional resin was not necessary for proper part manufacture with Thornel 50S/1004 when the 200 by 200 mesh fabric was used. Sufficient resin flowed from the composite into the mesh to encapsulate the coating fully and provided a smooth exterior panel surface.

The proper layup procedure for integral bonding is to apply the coating to the tool side of the part as described below. The actual cure may have to be adjusted according to panel thickness and the heat-up capability of the fabricator's equipment. This procedure was derived for 5- to 14-ply laminates.

Autoclave layup procedure is as follows:

- Lay up the resin-impregnated wire fabric against a release material that is against the tool plate. In the case where an adhesive film was used, the adhesive was laid against the release material and the fabric laid on the adhesive film.
- Lay up the high-modulus material against the wire fabric. When material containing scrim is used, the scrim cloth is to be down against the wire fabric.
- Continue until all plies are laid up.
- Locate a boundary support around the periphery of the layup. Gap between the panel and support should not exceed 1/2 in.
- Cover the layup with a separator fabric or film.
- Locate several plies of bleeder fabric over the separator sheet, but do not overlap the boundary supports. General rule: use one ply of bleeder per two plies of laminate.
- Cover the entire layup with three plies of style 120 glass fabric, then cover with vacuum bag.
- Cure in autoclave.

Materials used in these studies as separator films included perforated and nonperforated FEP (E. I. du Pont de Nemours and Company, Wilmington, Delaware). Boundary material was cork. Bleeder fabric was a nonwoven acrylic (CW 1850, West Coast Paper Company, Seattle, Washington). Titanium tools were used throughout.

It is necessary to lay up these parts with the fabric on the tool side since the positioning of bleeder material over the wire fabric will cause resin starvation of the latter because of the greater wicking action of bleeder fabrics.

Knitted wire fabrics were obtained from the Metex Corporation, Edison, New Jersey. The fabric employed was of 13 by 24 mesh density and a double-stranded 0.004-in.-diameter aluminum wire. This fabric was also integrally bonded to the laminates during manufacture. One ply of BP 907-impregnated, style 104 cloth was added to these laminates to provide additional resin for mesh bonding.

2.2.3 Silver-Pigmented Resin

Style 181 E-glass fabric was impregnated with a silver-filled epoxy resin by Epoxy Technology, Inc., Watertown, Massachusetts. This fabric forms the outer ply of panels and is incorporated as such during laminate manufacture. The silver-filled resin is marketed as EPO-TEK 410 LV. The manufacturer claims a volume resistivity of 0.001 to 0.003 ohm-cm for this product. Another Epoxy Technology product, EPO-TEK 417, was screened as an electrically conductive epoxy coating. This material, a paste, was applied by means of a doctor blade. The manufacturer claims a volume resistivity of 0.00005 to 0.00007 ohm-cm for this material.

Hysol conductive coating K9-4239, a sprayable material with a volume resistivity of 0.002 ohm-cm, was also screened as a protective coating.

2.2.4 Metal Fiber Layers

Metal fibers obtained from the Filaments group, Fiberfil Division, Rexall Chemical Company, Evansville, Indiana, were screened as an electrically conductive coating. The fibers, approximately 0.005 by 0.005 by 0.125 in., were aluminum. Coatings containing 0.04 and 0.08 lb of metal fiber per square foot were prepared by sprinkling the necessary quantity of fibers onto a single ply of BP 907-impregnated, style 104 scrim cloth. The layers were integrally bonded to the high-modulus composites.

2.2.5 Aluminiinized Glass Filaments

Aluminized glass filaments were obtained from the Lundy Technical Center, Lundy Electronics and Systems, Inc., Pompano Beach, Florida. The filaments were furnished on commercial textile cones containing 20-filament strands. Two types of material were obtained. In one, all 20 filaments were metallized; in the other, only 7 (of 20) were metallized. The filament consists of a metal thread bonded to a glass thread, as shown in Figure 2. Each thread is approximately 0.5 mil diameter. The filament uses the aluminum thread for electrical conductivity and the glass thread for mechanical strength.

Unidirectional layers of aluminized glass filaments were prepared by two procedures:

- The filaments were wound onto a single layer of BP 907-impregnated, style 104 glass cloth (224 strands per inch).
- The filaments were wet wound, impregnating them with BP 907 epoxy resin (448 strands per inch).

Using the partially metallized strands, the two layers contained 1550 and 3100 conductive filaments per inch, respectively. The scrim-containing layer has a cured thickness of 3.6 mils per ply, of which approximately 1 mil is the scrim cloth. A single ply weighs 3.4 lb/100 sq ft. The wet-wound layer is nearly 4 mils thick when cured and weighs 5.3 lb/100 sq ft. No fabrication difficulties were encountered with this material.

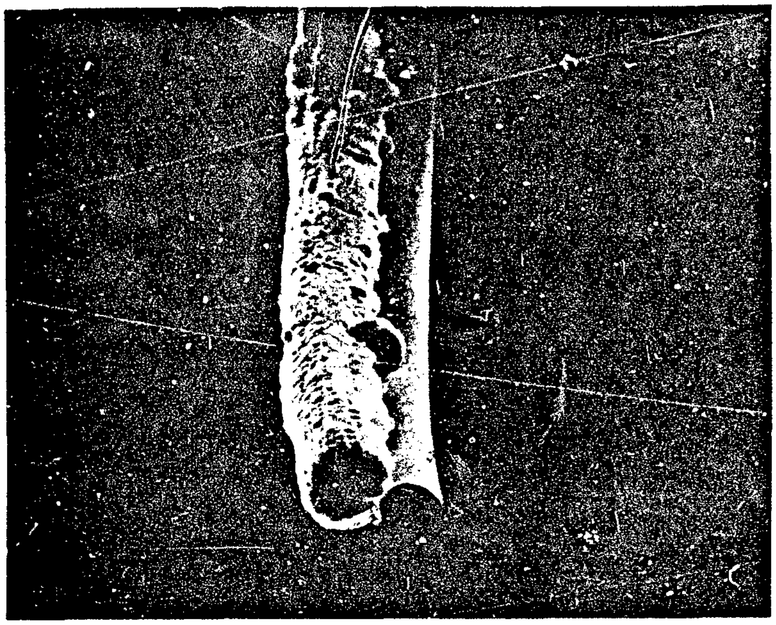


Figure 2. Aluminized Glass Filament (X 900)

The fully metallized strands were prepared by w^t-winding techniques only. These layers contained 4480 or 8960 conductive filaments per l' . inch. The cured layers were approximately 2.3 and 3.6 mils thick and weighed 2.2 and 3.o lb/100 sq ft/ply, respectively. The different cure schedules for boron and graphite did not change these properties.

Unidirectional layers of copper wires prepar. by the first procedure mentioned above were employed for control studies.

2.2.6 Miscellaneous Materials

Kapton film was obtained from E. I. du Pont de Nemours and Company, Wilmington, Delaware.

Style 104 glass scrim cloth impregnated with BP 907 epoxy resin, liquid BP 907 laminating resin, and unsupported BP 907 adhesive film were obtained from the American Cyanamide Corporation, Bloomingdale Dept., Havre de Grace, Maryland.

Nylon fabric was a standard peel ply material used in reinforced plastic manufacture. The material served as a bleeder and release agent and with but one exception (panel 298-299) was removed from the part surface after cure.

Primer coating for environmental paint coatings was P-158, a product manufactured by Andrew Brown Company, Los Angeles, and qualified to MIL-P-7962B. The lacquer topcoat was qualified to MIL-L-19537C and manufactured by the same company. The materials were applied per specification, except that the pretreatment coating MIL-C-8514 was not applied.

2.3 ENVIRONMENTAL TESTS

Coated and uncoated boron-filament- and graphite-fiber-reinforced laminates were exposed to the following environments:

- 140° F and 100% relative humidity
- Salt spray (3% NaCl)
- Immersion in hydraulic fluid (Skydrol 500A)
- Immersion in jet fuel (JP-4)
- Weather-O-Meter (FED-STD-141, method 6152)

Upon completion of these exposures, the samples were removed and subjected to artificial lightning discharges to determine if the environmental exposure altered the protective qualities of the coatings. In general, the coatings were not visibly altered by any of these environments, and all tests except salt spray were discontinued after 30 days' exposure.

3.0 LIGHTNING TESTS

3.1 LIGHTNING TEST APPARATUS

Past studies have shown that the damage introduced by a natural lightning stroke is composed primarily of two parts: a high-current component, which produces mechanical and electromagnetic damage, and a high-coulomb component, which causes thermal and electrical heating damage. The high-current discharge is usually a crest current with a peak amplitude from 10 to 200 kA and a pulse duration of up to approximately 50 μs. A high-coulomb component is usually a long-duration, low-amplitude current component (a few hundred milliseconds' to a few seconds' duration and from less than a hundred amperes to a few thousand amperes).

All aspects or properties of natural lightning cannot be simulated in the laboratory due to limited space and energy available as well as the lack of a complete understanding of a lightning stroke; however, for the present study, a test discharge with the following requisite characteristics was used:

- A high-current component rising from zero to a crest value of 200 kA in 10 μs and a pulse duration of 20 μs with ±50% tolerance on time
- A MIL-A-9094C, type-C, high-coulomb, transfer discharge with total charge transfer equal to or exceeding 200 coulombs in 2 sec or less

For the initial study phase of the development and formulation of coatings suitable for lightning protection of composite structures capable of surviving aircraft environments, a high-current component rising from zero to a crest value of 100 kA is 10 μs and a pulse duration of 20 μs with ±50% on time was used. Application of this moderately severe stroke not only screened coating candidates for further study, but also aided development of protective coatings for areas requiring only secondary protection such as the zone II or III areas of an airplane (Ref. 4).

The laboratory test setup is shown in Figure 3. The test panel was clamped to an 18- by 18-in. phenolic panel that was bolted to the Faraday cage and was electrically isolated from the cage except for the ground strap clamped to one end of the panel. This configuration ensured that the discharge current passed through the maximum available coating surface of a test panel. A 1/4-in.-diameter tungsten probe was used to direct the discharge to the test panel and a 1/4-in. gap was maintained between the probe and the panel.

The Faraday cage, a metallic box to provide electromagnetic shielding, was used not only to hold the test panel during the discharge, but also to house test equipment for the electromagnetic penetration measurement task discussed in section 4.3.

3.2 HIGH-CURRENT GENERATOR

The energy source used to generate a 100-kA crest was provided by a 42 μF capacitor bank with a positive-grounded power supply, i.e., the discharge probe injected discharging electrons toward the test panel to simulate a more severe damage situation than that of a

positive probe, should the system have a negative-grounded power supply. The capacitor bank normally produced an underdamped oscillatory discharge. The required single-pulse discharge was produced by shunting or diverting the discharge current parallel to the test panel immediately after the first half cycle of the oscillatory discharge. This effectively impressed a single-pulsed discharge on the panel even though the capacitor bank continued to discharge in an oscillatory manner. Referring to Figure 4, the capacitor bank was discharged through the test panel in an oscillatory condition by closing switch S_1.

However, at the moment the first half cycle of the discharge was completed, switch S_2 was closed. This shunted the current away from the test panel and to ground via a parallel circuit. The discharge current was measured by a high-current shunt made by The Boeing Company. The output of this shunt was connected to a Tektronix 549 storage oscilloscope, which allows photographic records of the discharge current to be made.

The diverting switch S_2, a General Electric 27207 ignitron tube, was turned on by a high-voltage pulse at a predetermined time. Ideally, closing the diverting switch should have shunted the discharge current and stopped all current flow through the test item. However, since both the ignitron tube and the test panel have finite impedances, the current was shared between them. Although the impedance of the parallel diversion circuit was low enough to give the simulated lightning discharge the desired unipolar characteristics, it could not be used to trigger high-coulomb discharges and would not reliably work at 200-kA discharge levels.

An improved switching technique was developed with Boeing research funds. It not only gives reliable 200-kA discharges and can be used as a unipolar trigger for high-coulomb discharges, but also prevents current flow after the initial unipolar pulse. The schematic diagram of the laboratory setup is shown in Figure 5. This setup differed from the one previously used

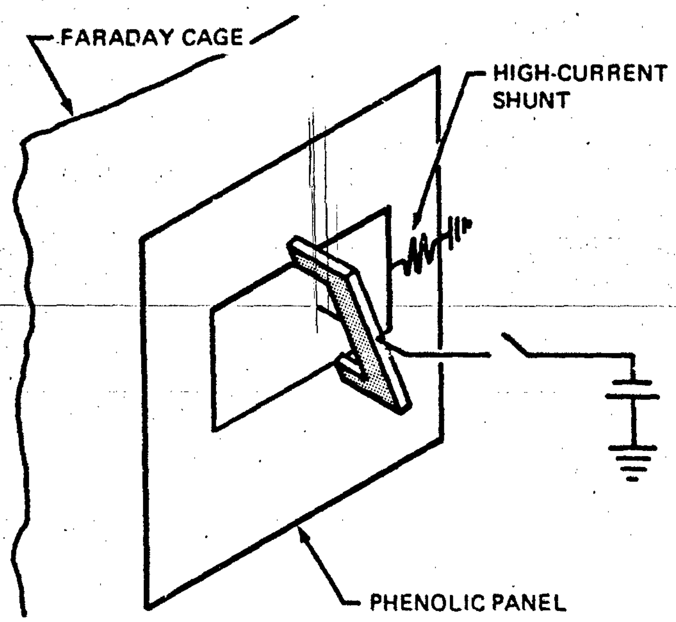


Figure 3. Laboratory Test Setup

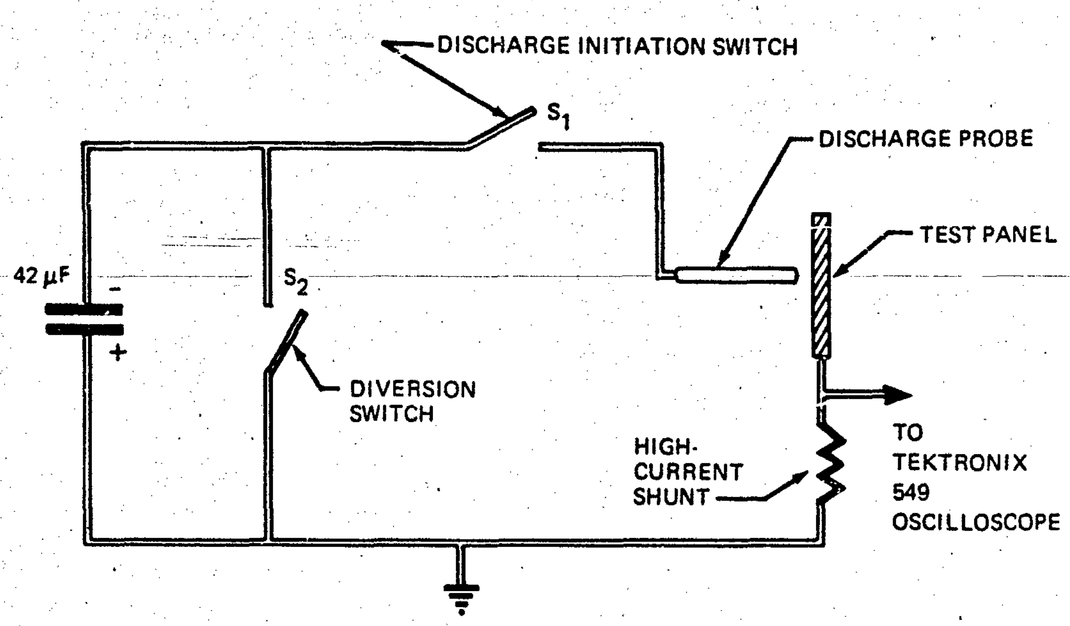


Figure 4. Schematic Diagram of the High-Current Test Setup

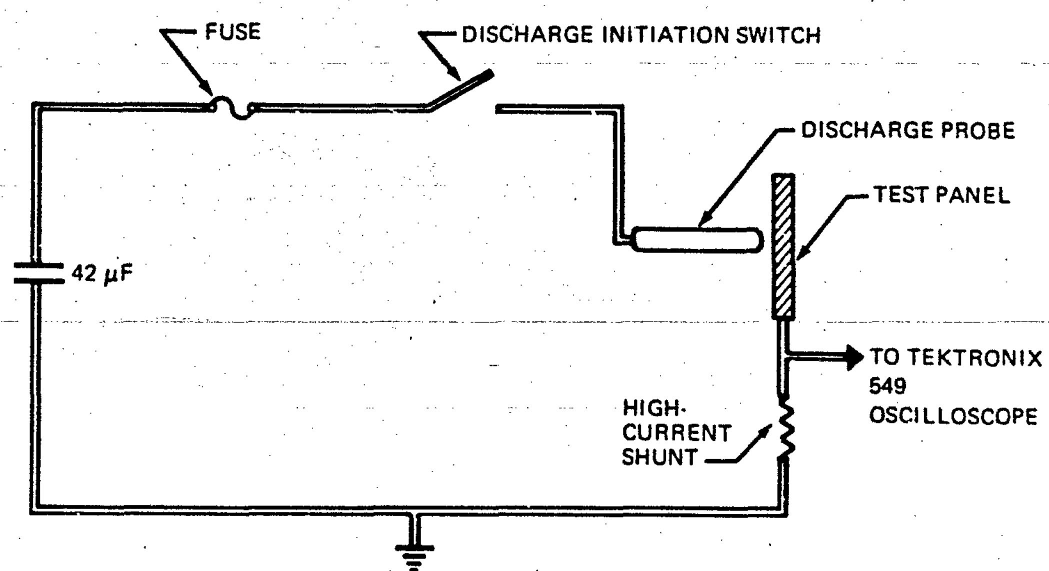


Figure 5. Schematic Diagram of Modified Test Setup

in that the shunting ignitron switch was replaced by a series fuse. The initial current surge from the capacitors caused the fuse to fail. This opened the circuit and prevented current flow after the first half cycle. Through a unique design, very little series inductance was introduced into the discharge circuit by adding the fuse. The design also prevented formation of a plasma arc that, in many fuse-type switches, provides a current path after the first half cycle and results in a damped oscillatory waveform.

Oscillograph displays obtained during the testing of protective coatings for both 100- and 200-kA discharges are shown in Figure 6. Some oscillograph traces obtained using the ignitron switch are also displayed, for comparison. Note that the coatings on the test samples are low impedance and present the most difficult condition for obtaining a unipolar discharge. The fuse switch was used on all tests performed after September 1, 1971.

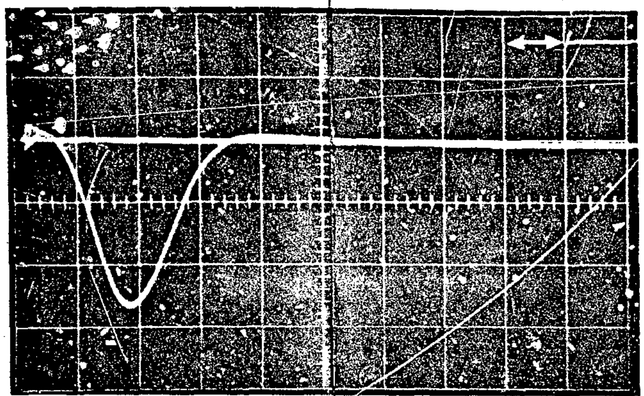
3.3 TWO-COMPONENT GENERATOR

A block diagram of a two-component lightning generator is shown in Figure 7. The high-current component generator first established an arc between the discharge probe and the test item; the high-coulomb component generator then followed on by discharging a dc component through the established ionized channel to the test panel. The charged high-voltage capacitor bank was isolated electrically from the battery bank by switch S_1; these high-current and high-coulomb components were isolated transiently from each other by the isolation coil. The total discharge was terminated by opening switch S_T.

Two 430-V battery carts were used for the required high-coulomb component. Each steel cart measured 73 by 49 in. and was 50 in. high, had 36 automotive batteries (12 V), and a total weight of about 2200 lb. With a series connection, the system was capable of discharging a dc level up to 700 A and maintaining an arc with a gap of up to a half inch.

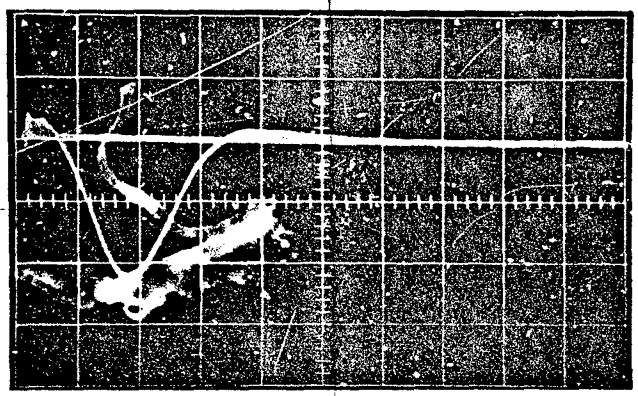
Prior to September 1, an oscillatory system was used, instead of the diverting discharge system, with the same [illegible]-μF capacitor bank. This was necessary because the high-coulomb component currents from the battery bank would otherwise have flowed through both the diversion switch and the discharge path; the excessive dc current that flowed through the diversion switch would not only have degraded the available testing energy, but also would have greatly reduced the lifetime or damaged the ignitron tube. The extra coulomb value provided by the additional discharge from the capacitor bank was less than 1% of the total amount of the two-component stroke.

The development of a series fuse switch allowed high-coulomb discharges to be triggered with a unipolar high-current discharge. This was possible because the associated circuit of the discharge generator with the series fuse had no shunting components. Figure 8 shows the oscillograph displays of the high-current trigger and the high-coulomb discharge obtained in testing panel 475-GP84-AF05C-0000. All high-coulomb discharges made after September 1, 1971, were triggered with a unipolar discharge.



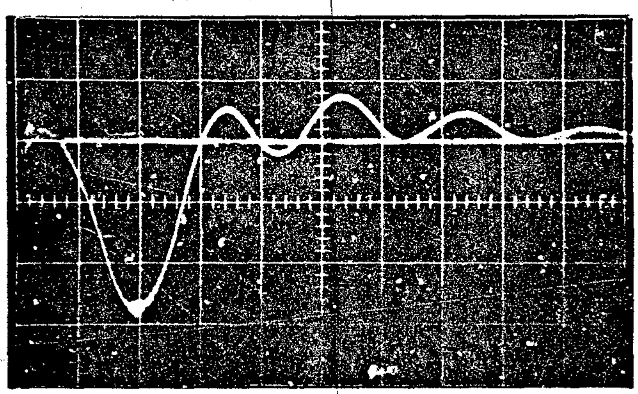
10 μs

481-GR18-AI09N-ALCO
PEAK CURRENT—100 KA

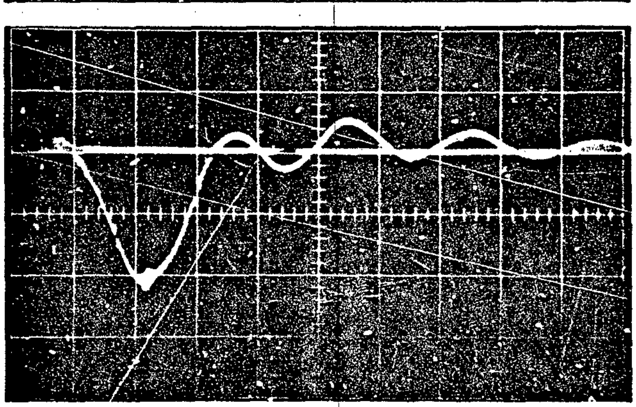


484-GP87-AI09N-ALCO
PEAK CURRENT—200KA

a. TRACES USING FUSE SWITCH



436-BR94-AI05N-0000
PEAK CURRENT—109 KA



458-GP73-AC03C-AR04Z
PEAK CURRENT—196KA

b. TRACES USING IGNITRON SWITCH

Figure 6. Oscilloscope Traces

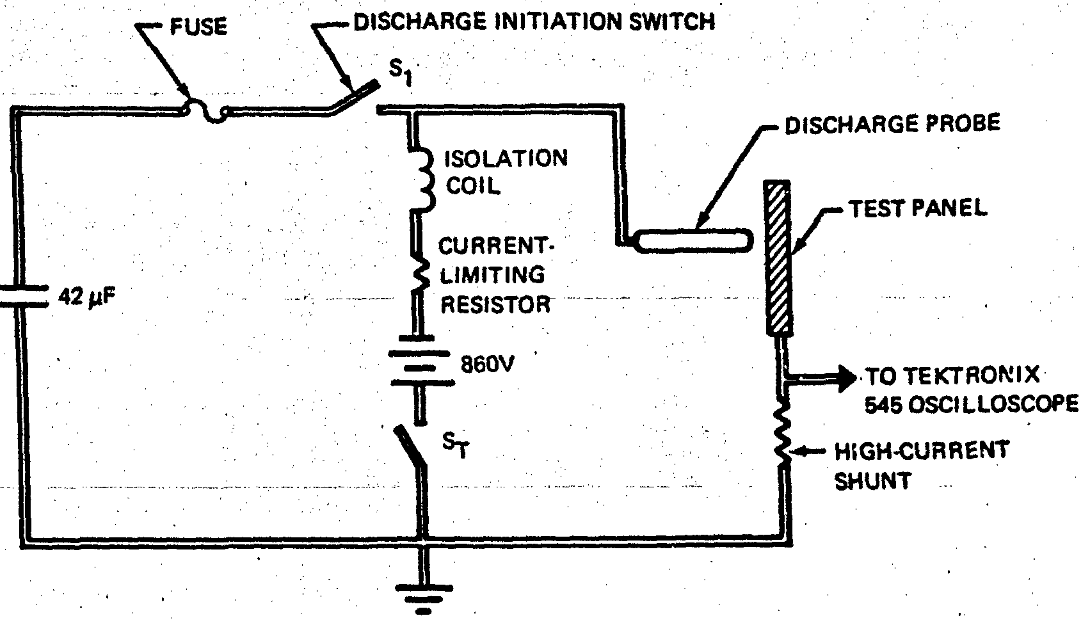


Figure 7. Schematic Diagram of Two-Component Generator

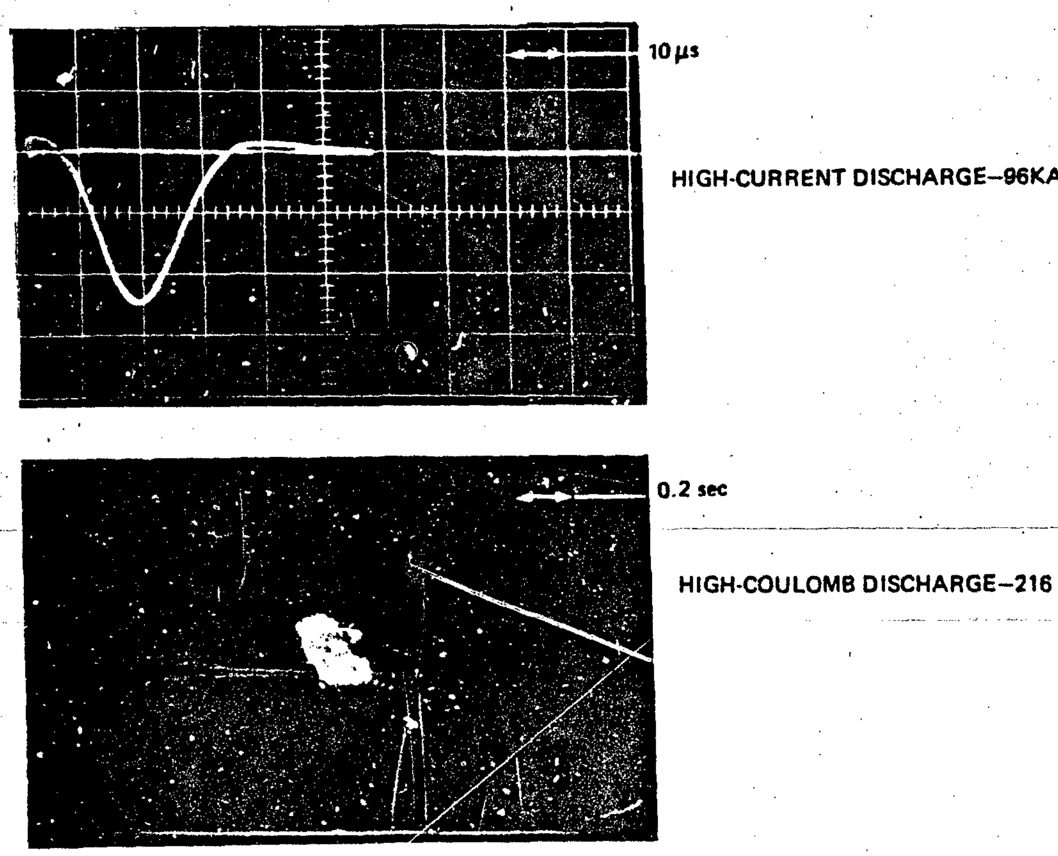


Figure 8. High-Current, High-Coulomb Oscillograph Traces

4.0 ELECTRODYNAMIC EFFECTS

4.1 TRIBOELECTRIC CHARGING

Triboelectric charging results from an imbalance of charge that occurs when two materials are separated. This will occur on an aircraft if the surface is exposed to atmospheric aerosols and hydrometeors. The amount of charge produced is a function of aerosol concentration, aircraft speed, type of material, and surface condition. All materials, whether dielectric or conductor, are subject to triboelectric charging. The problem of radio noise occurs when the charge is accumulating at a rate faster than it can leak off through the resistivity of the material. The charge will accumulate until a potential equal to the breakdown strength of the surrounding atmosphere is reached and a radio-noise-producing streamer is produced. (Radio noise may also be produced when the total charge accumulation on an aircraft due to triboelectric charges on its frontal surfaces raises the aircraft potential to the point where discharges occur from its extremities; however, this is beyond the scope of this discussion.)

The problem is not how the charge is produced, but rather if it is stored on the surface. Structures that consist of thin dielectrics over conducting materials will store charge. However, because the maximum storage potential is limited by the voltage breakdown strength of the dielectric, maximum energy and the resulting radio noise are much reduced compared to radome-like structures. This is the case with the coatings recommended for use on composite structures in this report.

Coated panels were placed in a high-velocity stream of Wonda flour particles and subjected to triboelectric charging. Figure 9 is a diagram of the equipment setup. The sample was mounted 3-1/2 in. above an aluminum ground plane on polyfoam pedestals. The grounding ring, made from copper tape, was placed around the periphery of the sample to collect charge. The charge collector was connected to ground through a 10,000-ohm resistor. Voltage waveforms were displayed on a Tektronix 585 oscilloscope using a 10 to 1 voltage divider probe across the 10,000-ohm resistor. A photograph of the equipment is shown in Figure 10.

When the charge accumulation on the surface of the dielectric reached a potential equal to or greater than the breakdown potential of air, a discharge occurred to the collector ring. The charge then leaked off through the 10,000-ohm resistor. An equivalent circuit of the discharge is shown in Figure 11. The streamer discharge is represented as a transfer of charge from a low-capacitance region on the dielectric (C_s) through the resistance of the streamer (R_s) to the equivalent capacitance of the collector ring (C_d) and oscilloscope. The charge eventually reaches ground through the resistor (R_d). The effective capacitance of the charge on the dielectric is thought to be less than 1 $\mu\mu$F. The equivalent resistance of the streamer discharge is 5000 ohms (Ref. 5).

The mechanism of the discharge was different when the dielectric surface was a thin film of nonconducting material bonded over a conducting material. In this case, the surface charge accumulated until the potential was great enough to puncture the dielectric film. Surface potentials are naturally less than those produced on solid dielectrics. The voltage at the 10,000-ohm resistor was less, since the capacitance of the collector ring and conducting material was greater than the capacitance of the collector ring alone.

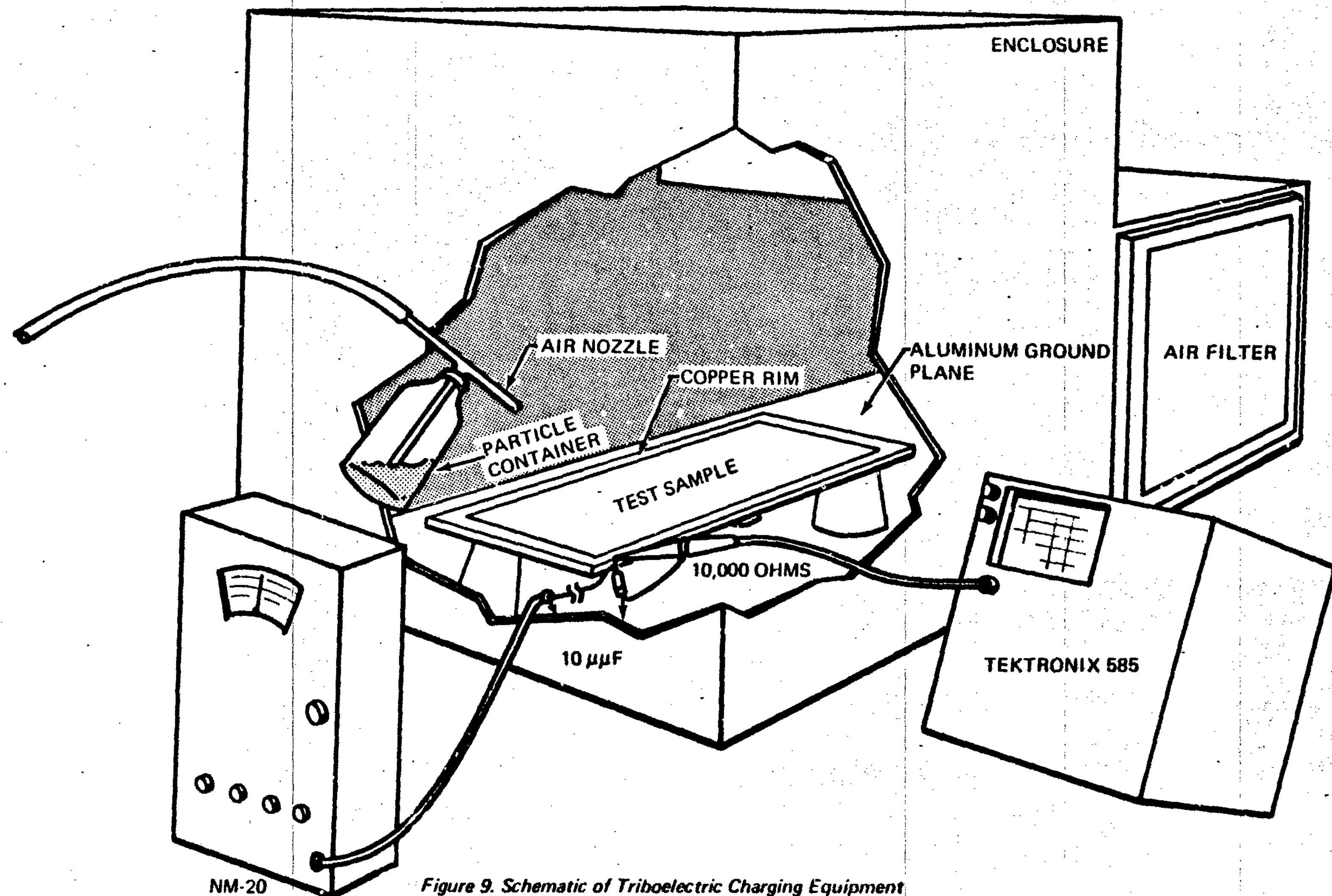


Figure 9. Schematic of Triboelectric Charging Equipment

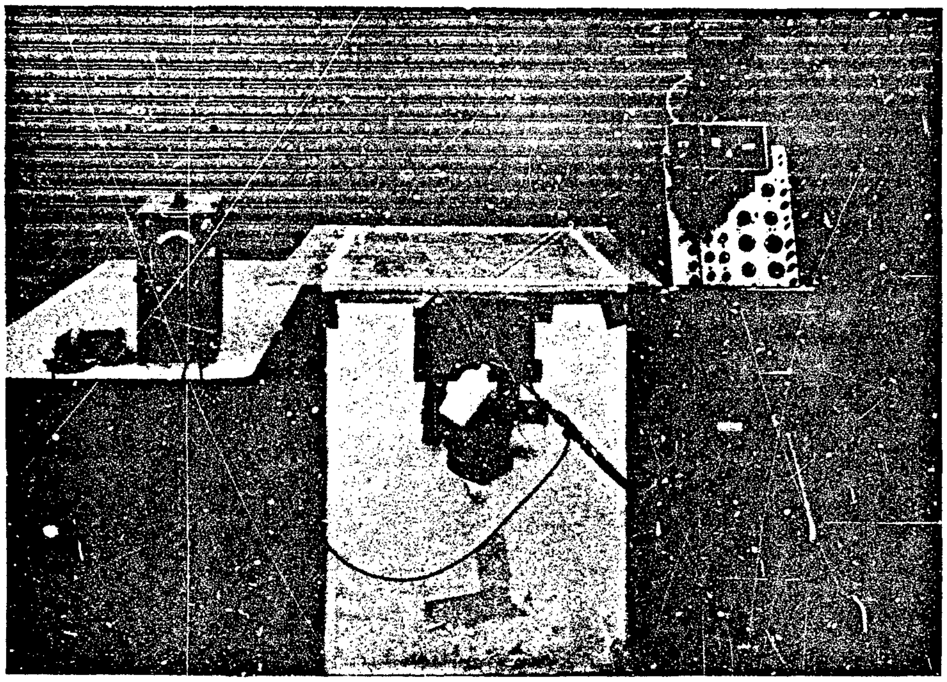


Figure 10. Triboelectric Charging Test Setup

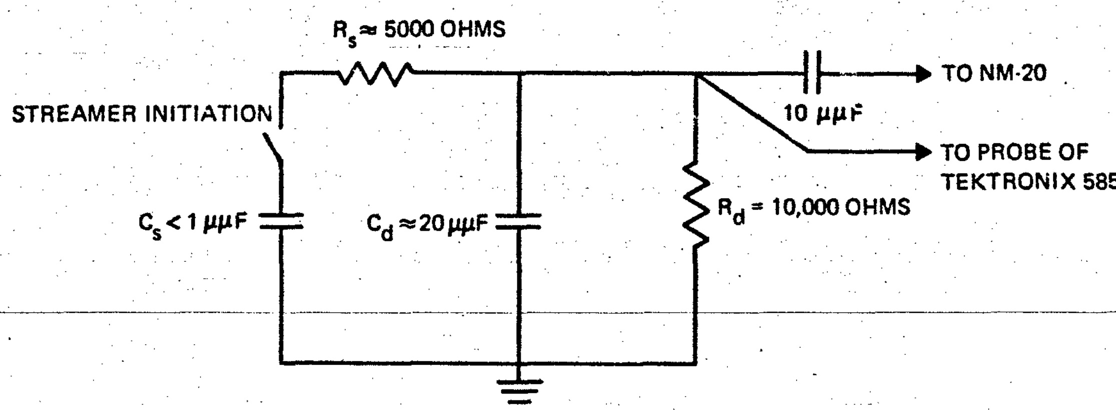


Figure 11. Equivalent Circuit of the Streamer Discharge

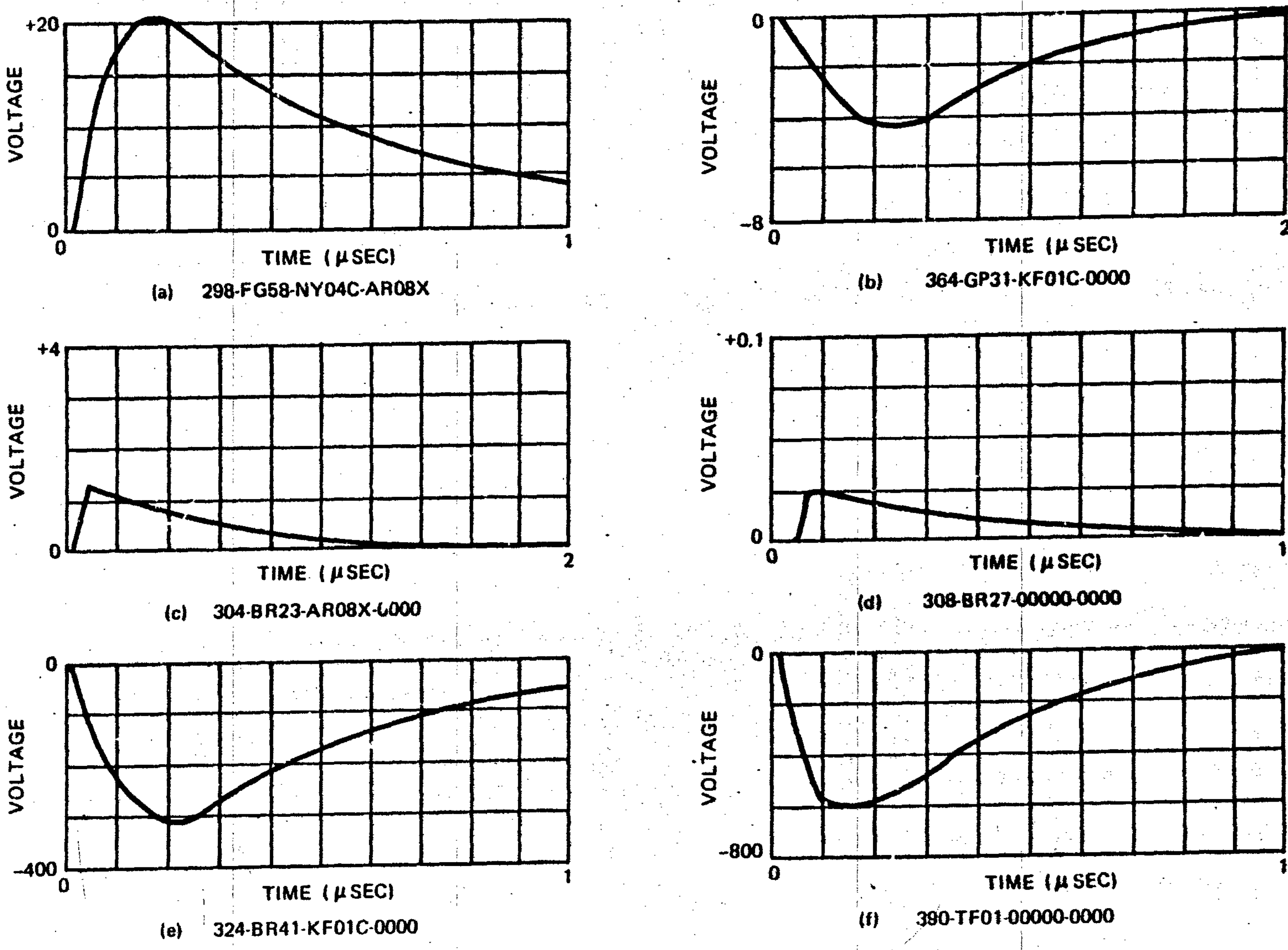
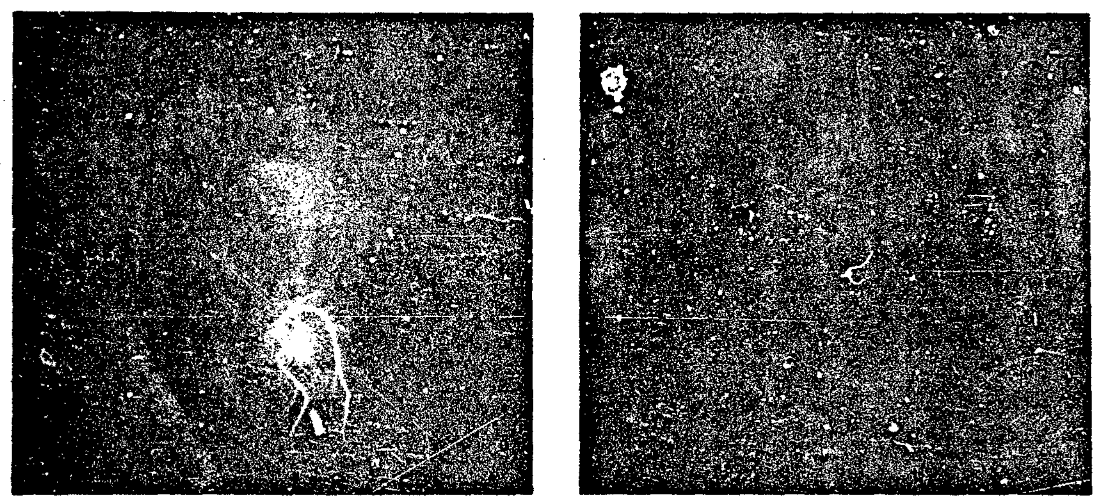


Figure 12. Pulse Waveforms of Panels Subjected to Triboelectric Charging

Panels 292 through 311, 324 and 325, and 336 and 343 have been tested for static charge accumulation. Only the following panels displayed signs of charging activity:

Panel	Peak Noise, dB (400 kHz)
298-GP58-NY04C-AR08X	90
364-GP31-KF01C-0000	35
304-BR23-AR08X-0000	10
308-BR27-00000-0000	10
324-BR41-KF01C-0000	70
390-TF01-00000-0000	80

Figure 12 illustrates the maximum waveforms obtained for these panels. Figure 13 shows the streamers produced on panels with nonconductive surface coatings of nylon-fabric-impregnated epoxy (a) and Kapton film (b).



(a) 298-FG58-NY04C-AR08X (b) 364-GP31-KF01C-0000

Figure 13. Streamer Discharges Produced on Panels 298 and 364

The relative radio noise was measured by connecting the input of a Stoddart NM-20 radio interference frequency intensity meter, tuned to 400 kHz, to the 10,000-ohm resistor with a 10 $\mu\mu$F capacitor. The peak intensity in decibels above set noise caused by the static discharge is recorded above.

Panels 500 and 509 through 514 were also subjected to static charge accumulation tests. These panels were representative of the coating systems recommended for advanced composite materials. These panels did not display any signs of charging activity.

Uncoated, boron-filament-reinforced epoxy laminates are subject to triboelectric charging; however, the magnitude of the effect observed was minor compared to that produced on a low-loss dielectric such as Teflon. No charging effects were observed on uncoated, graphite-fiber-reinforced epoxy laminates. A 1-mil coating of Kapton film over either high-modulus composite presented a surface subject to an objectionable level of triboelectric charging.

The triboelectric charging measurements indicated that it is inadvisable to use thin films of dielectric materials over conductive composites. This is especially true for areas where particle impact would be prevalent (nose radomes, leading edges, etc.). Streamers across dielectric films are not only a possible source of radio interference, but also puncture the film allowing possible coating degradation.

Conductive coatings relieve high-modulus composites of their charging tendencies. The acceptable charging characteristics observed with these coated composites were due to the low-volume resistivity of the coating. The coatings did not charge to sufficient potential to support a streamer discharge capable of causing radio interference.

4.2 ELECTROMAGNETIC SHIELDING

The H-field shielding effectiveness of 12- by 12-in. coated and uncoated test panels was measured at both high and low frequencies. Figure 14 shows the test equipment used for the 1- to 1000-kHz shielding effectiveness measurement. It consisted of coaxial transmitting and

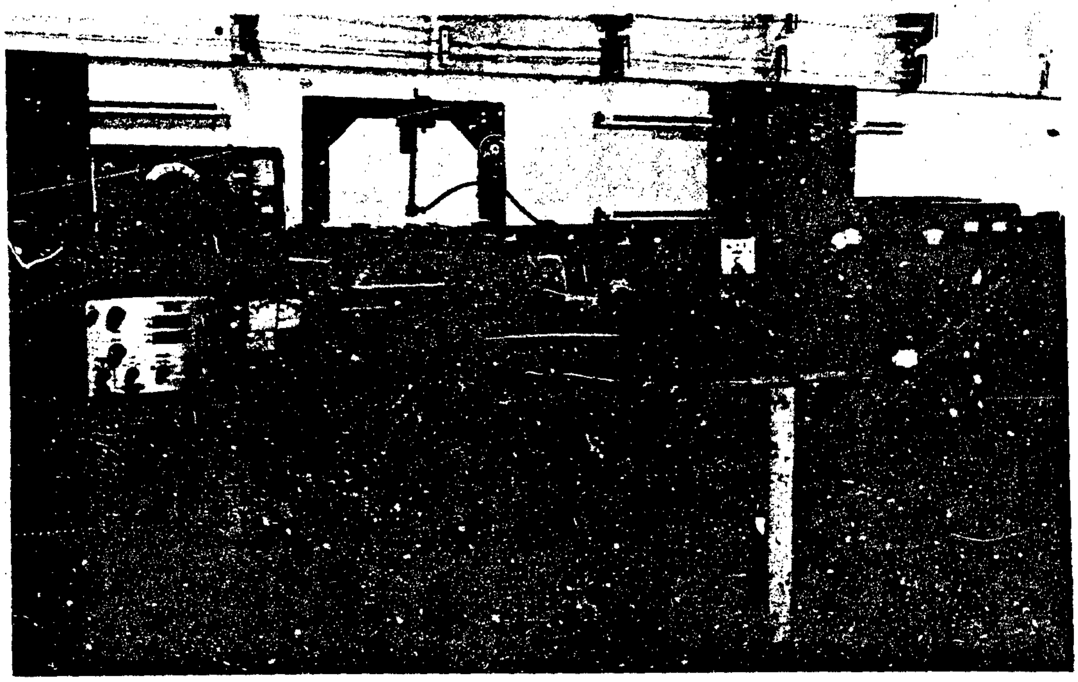


Figure 14. Low-Frequency Shielding Effectiveness Equipment Setup

receiving coils 4 in. apart, with axes perpendicular to the plane of the test panels. The coils were constructed using 20 turns of no. 22 copper wire on a 3/4-in.-diameter, 1/2-in.-long bobbin. A nonmetallic structure was used to mount the coils and test panels. The transmitting coil was excited with a suitable oscillator and power amplifier (Hewlett-Packard 200DC or 606A); the receiving coil was connected by RG 55/U cable to the 50-ohm input of an appropriate electromagnetic interference (EMI) instrument (Electrometrics EMC-10 or Stoddart NM-12T or NM-25T).

After the operator had established the lack of extraneous coupling, the test procedure was to establish a reference reading at the desired frequency on the EMI instrument with the test panel absent. Then the panel was inserted (center on coil axis) and a new reading determined. The difference in readings (in decibels) represented the magnetic shielding of the test panel at that coil spacing. The shielding effectiveness of several panels is plotted on Figures 15 through 17.

The procedure was extended to higher frequencies by using a shielded coil and a much closer coil spacing. The basic change in the equipment was the use of one-turn, shielded coils spaced 0.4 in. apart. The coils were 3/4 in. in diameter and constructed from 1/8-in.-diameter, solid-shield, copper coaxial cable. Shielding was necessary to eliminate the electric field coupling between coils that exists at the higher frequencies. The closer coil spacing minimized magnetic coupling around the edge of the test panel and also provided an adequate dynamic range for the measurement. The test procedure was similar to that of the low-frequency measurements. The relative H-field shielding effectiveness obtained at the high frequencies is shown in Figures 15 through 17.

The results of the electromagnetic shielding measurements were verified by theoretical analysis. The relative dc conductivity of a 1-mil aluminum panel and two uncoated graphite panels was measured using standard procedures. This was accomplished by passing a known current through a narrow strip (approximately 1/4 in. wide and 12 in. long) cut from the center of the panels and measuring the voltage developed across a pair of independent electrodes located a known distance apart along the strip. These measurements yielded a relative conductivity of 0.543 for the 1-mil aluminum panel, 0.000382 for the 14-ply graphite panel, and 0.000417 for the 5-ply graphite panel.

Theoretical values for shielding effectiveness were obtained using the following equation, which can be derived by the transmission-line approach (Ref. 6):

$$S_H = A + R + B \text{ (dB)}$$

$$A = 131\, t \sqrt{\mu_R\, \sigma_R f}$$

$$R = 20 \log_{10} \frac{|1 + k|^2}{4|k|}$$

$$B = 20 \log_{10} \left| 1 - \left(\frac{k-1}{k+1}\right)^2 10^{-0.10A} e^{-j0.23A} \right|$$

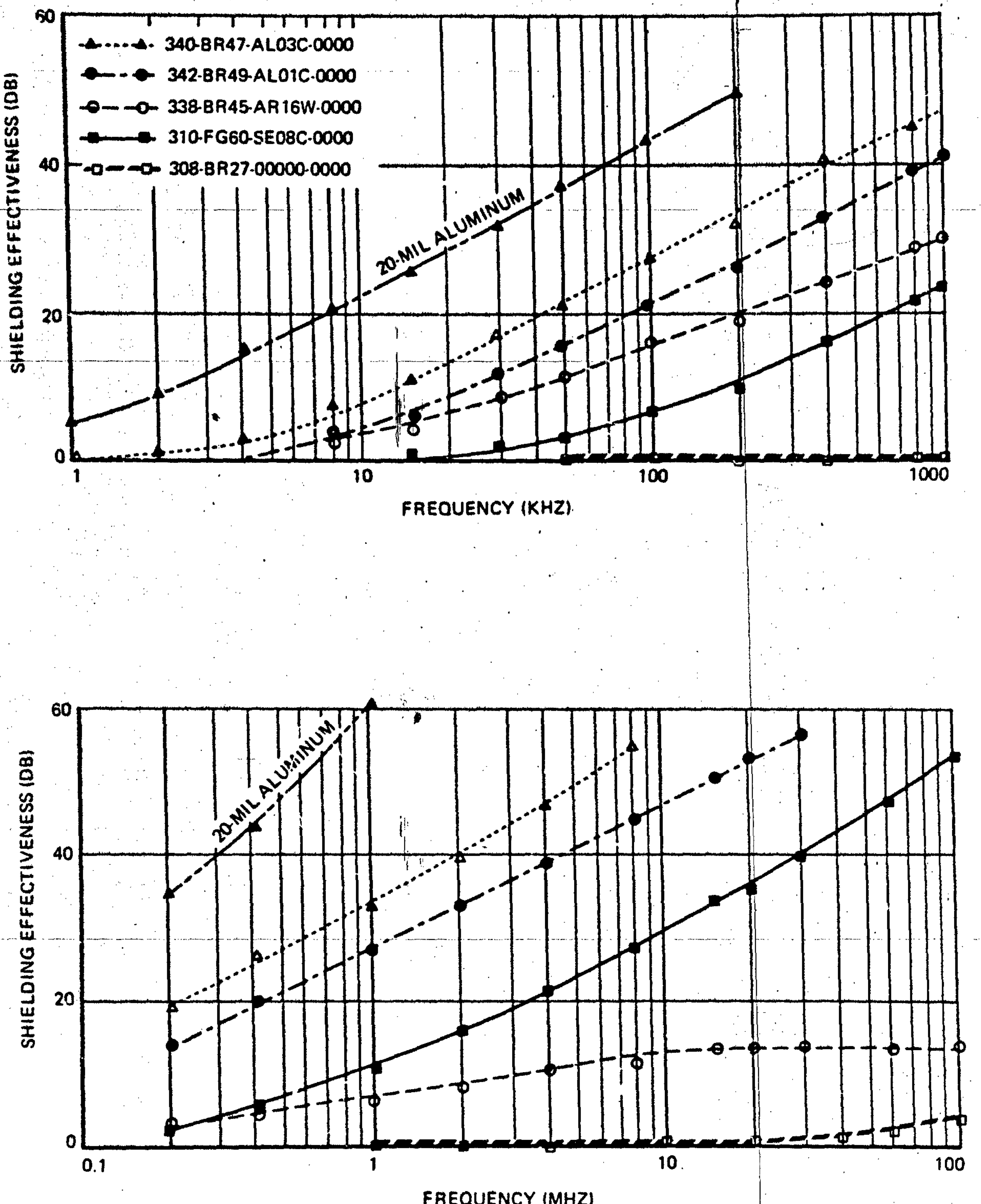


Figure 15. Shielding Effectiveness of Panels 308, 310, 338, 340, and 342

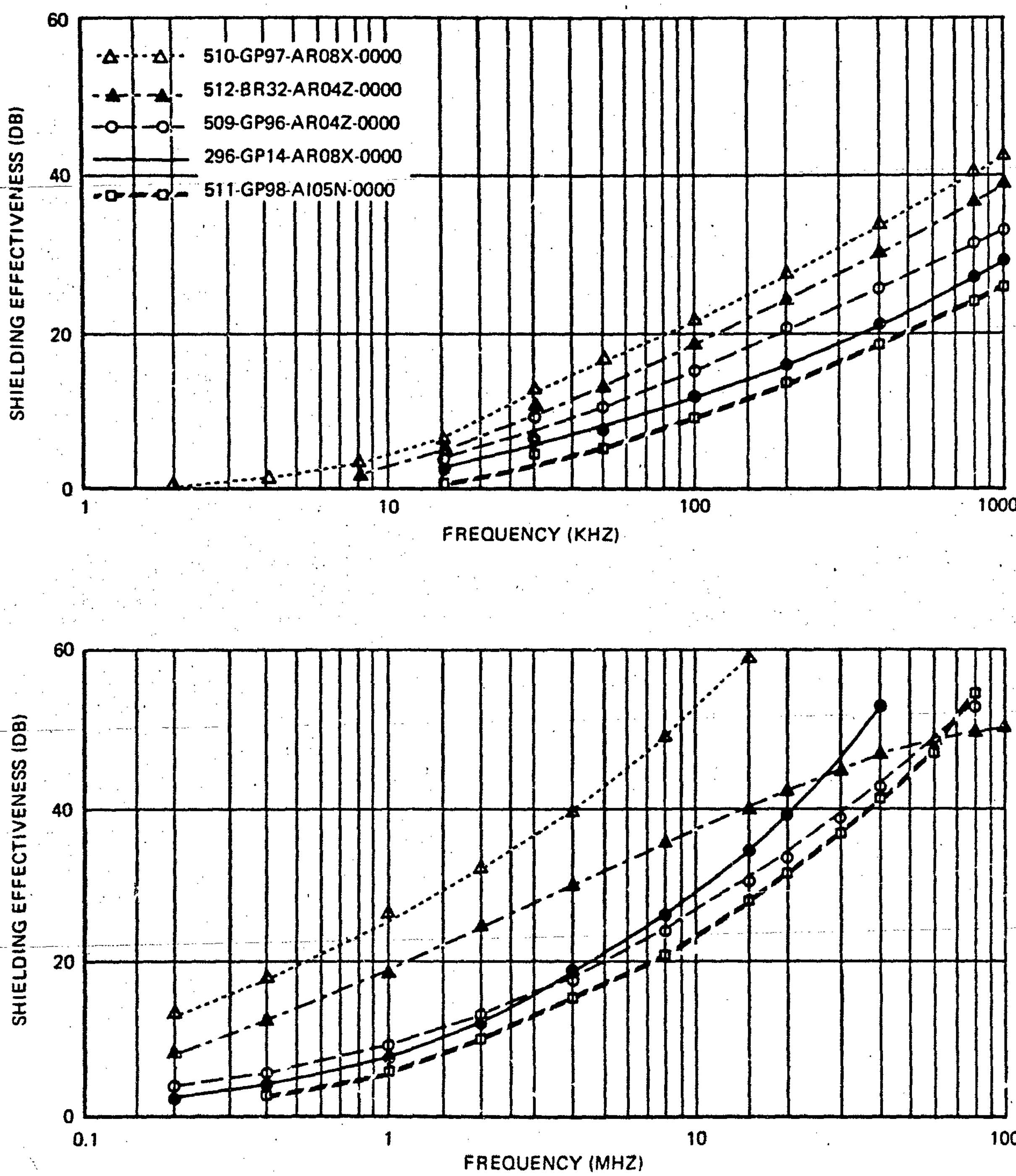


Figure 16. Shielding Effectiveness of Panels 296, 509, 510, 511, and 512

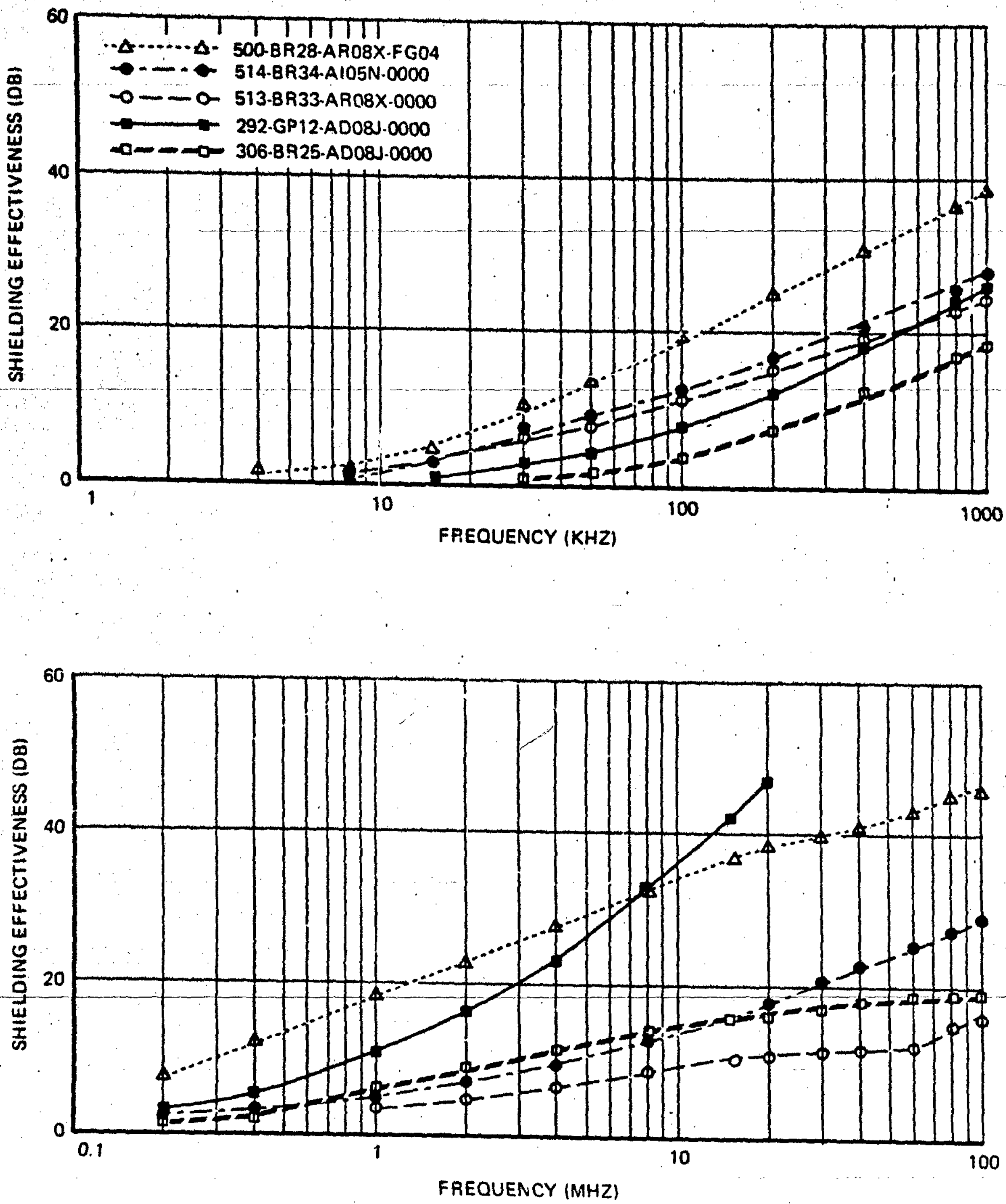


Figure 17. Shielding Effectiveness of Panels 292, 306, 500, 513, and 514

where

$$k = (1+j)|ZW|\,1.915 \times 10^{6}\sqrt{\sigma_R/f\mu_R}$$

$$\frac{ZW}{jf} = 7.9 \times 10^{-6} r$$

f = frequency, Hz

t = shield thickness, meters

$2r$ = loop-to-loop distance, meters

μ_R = permeability of shield material relative to vacuum

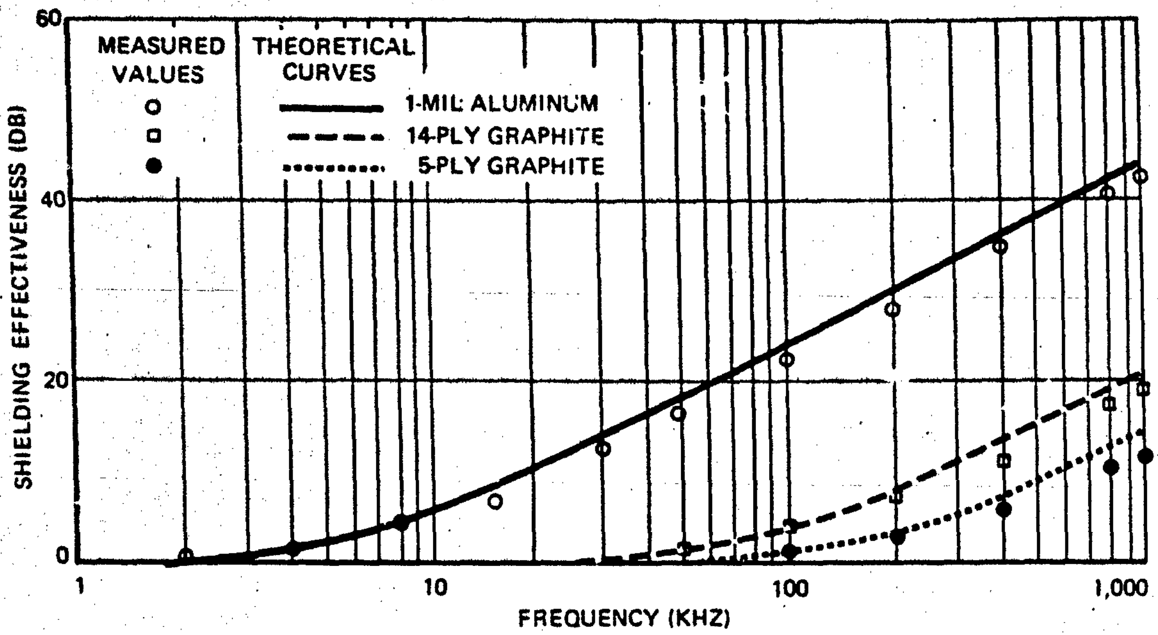
σ_R = conductivity of shield material relative to copper

Figure 18 shows the measured shielding effectiveness and the theoretical shielding effectiveness for the aluminum and graphite panels. The agreement between the measured values and the theoretical values validates the results of the shielding measurements. This confirms the obvious conclusion that the uncoated composites have little or no shielding effectiveness. The uncoated, boron-filament-reinforced control panel displayed no shielding at frequencies less than 10 MHz. The uncoated, graphite-fiber-reinforced panel displayed some shielding at all frequencies. Woven wire fabric coatings provided a degree of shielding, but not as much as that observed in comparable densities of aluminum foil. Within the mesh densities investigated, the heavier wire diameters appeared to be the more efficient. None of the coatings provided the degree of shielding achieved with thin-metal panels (0.020-in.-thick aluminum).

Careful consideration of the shielding effectiveness displayed by the curves revealed an inconsistency in the measurements conducted on panels of similar construction. For instance, the shielding effectiveness measured on panels 510 and 296, both graphite panels using the same protective coating, differed by as much as 25 dB at some frequencies. A similar discrepancy is displayed by the data of panels 500 and 513. Also, it is curious that the boron panel coated with aluminized glass fiber, panel 514, showed better shielding effectiveness at low frequencies than graphite panel 511 with the same coating. The variance in shielding effectiveness of panels of similar construction may have been due to a difference in the amount of contact between the conductive elements of the coating. This possibility is discussed further in section 4.3.

4.3 ELECTROMAGNETIC PENETRATION

The electromagnetic penetration of electrical energy through the coating systems was measured by applying a 40-kA discharge to the center of a 12- by 12-in. panel mounted in the opening of the Faraday cage and sensing the penetrating field with an orthogonal loop. The bond between the panel and the Faraday cage was ensured by clamping a 1-in.-wide braid in the periphery between the face of the Faraday cage and the panel. The panel at the contact area was lightly sanded to expose the conductive elements of the coating. The pickup loop was made with 13 turns of 1/16-in. rigid copper coaxial cable bent to form a toroid. The outer conductor of the coaxial cable was used to provide shielding of the electric field. A



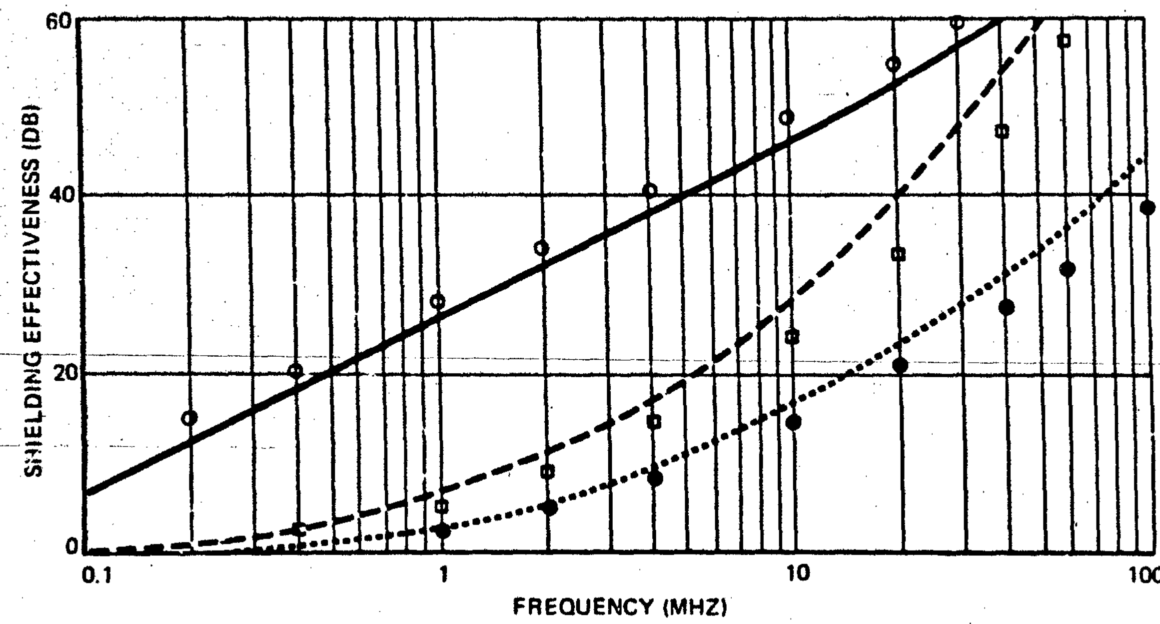


Figure 18. Measured and Theoretical Shielding Effectiveness

small circumferential cut at the midpoint of the shield prevented shorting the magnetic field. The center conductors at the ends of the loop were fed to the inputs of a differential amplifier through shielded twinax cable. The pickup loop was placed on the inside of the Faraday cage 3/8 in. from the back of the panel directly behind the point of arc attachment.

Preliminary tests were performed to verify the shielding of the Faraday cage by using aluminum test panels 0.063 in. thick. Testing also indicated that the shielding capability of the panel was greatly impaired if the discharge was of such a magnitude that a hole was produced in the coating. Therefore, discharges of less than 50 kA were used since repeated testing of each panel was necessary to obtain the required data. Because 1-mil aluminum foil would puncture at these levels, 10-mil aluminum was used as the standard for comparison.

The loop configuration and its orientation with respect to the discharge probe located the axis of the individual turns orthogonal to the induced current flow (Fig. 19). The configuration also made any effects due to nonsymmetry of the current flow from the arc attachment point to ground negligible. A photo of the loop from within the Faraday cage is shown in Figure 20.

Panels 500 and 509 through 514 were tested for electromagnetic penetration along with a 10-mil aluminum control sample. A 40-kA discharge was applied to the center of each panel. An oscillating discharge was used since it made the interpretation of the data simpler. The voltage pulses received on the loop were recorded on a storage oscilloscope. The current through the shunt was also recorded on a storage oscilloscope to ensure that the current level applied to the coated panels was the same as that applied to the control panel. The peak voltage obtained for each panel is given in Table 1.

Table 1. Results of Electromagnetic Penetration Tests

Panel	Electromagnetic penetration		Shielding effectiveness (dB at 33 kHz)	
	Relative voltage	Relative dB	Obtained before penetration tests	Obtained after penetration tests
10-mil aluminum control	0.1	28	28	28
500-BR28-AR08X-FG04	0.5	14	10.5	NA
509-GP96-AR04Z-0000	1.2	6.5	8	9
510-GP97-AR08X-0000	0.8	10	13	12.5
511-GP98-AI05N-0000	0.3	18.5	3	9.5
512-GR32-AR04Z-0000	1.3	6	10	9
513-BR33-AR08X-0000	0.4	16	7	12
514-BR34-AI05N-0000	0.5	14	7	9

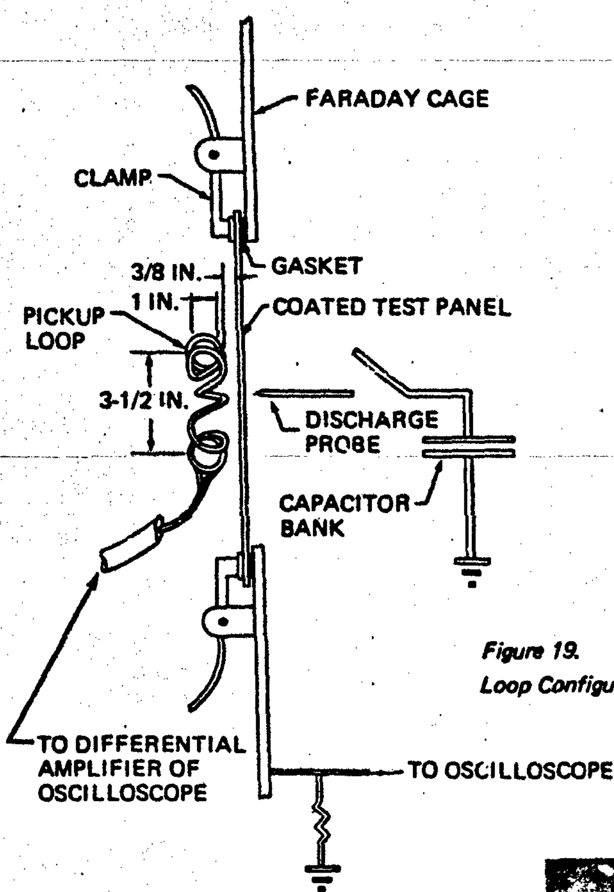


Figure 19.
Loop Configuration for Electromagnetic Penetration Test

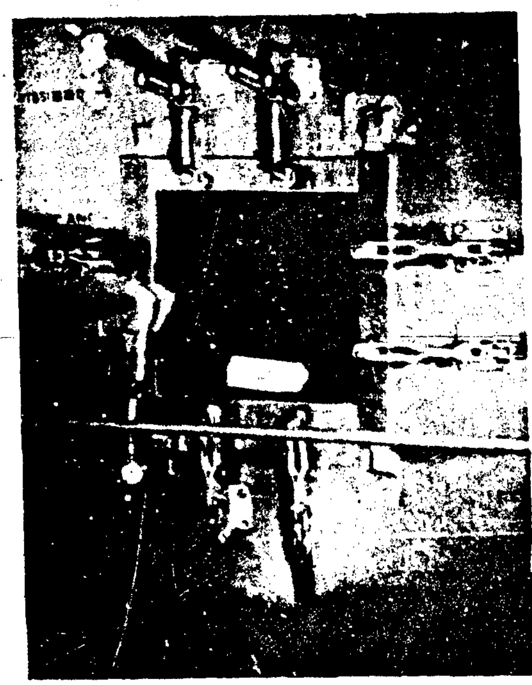


Figure 20.
Pickup Loop Shown From Within Faraday Cage

Since the test discharge had a 30-μs period, the data should agree with the shielding effectiveness, section 4.2, obtained at 33 kHz. The shielding effectiveness of the 10-mil aluminum control panel was measured and found to be 28 dB at 33 kHz. These data were used to establish a relation between the electromagnetic penetration measurements and the effective shielding measurements by equating the 0.1 V obtained for the 10-mil aluminum panel in the penetration tests with the 28 dB measured for shielding effectiveness of the 10-mil aluminum panel at 33 kHz. The penetration in dB relative to the control panel is given in Table 1. Table 1 also shows the shielding effectiveness of the panels measured before the electromagnetic penetration tests were conducted.

In general, the results of the electromagnetic penetration measurements were comparable to the data obtained by the shielding effectiveness measurements. However, three panels, 511, 513, and 514, show gross error. It was suspected that some physical change may have taken place in the structure of the panels as a result of the discharges. The panels were therefore remeasured for shielding effectiveness at 33 kHz. These data are also presented in Table 1.

The data clearly show that a change in the structure of the coating has taken place. The change of the panels was further explored by remeasuring the panels with the high-frequency shielding measurement set up at 0.2 and 4.0 MHz. The close spacing of the coils used in this equipment setup enabled the shielding effectiveness to be measured over small areas of the panel and allowed investigation of the shielding effectiveness at and near the arc attachment point. These measurements indicated that the two or three 40-kA discharges applied to the coated panels during the electromagnetic penetration test fused the separate conducting elements together and increased the shielding effectiveness in some areas and, by melting, broke the continuity of some elements and reduced shielding effectiveness at the arc attachment point. As indicated in section 4.2, coatings made from identical materials and procedures varied greatly in their shielding effectiveness. Some of the woven wire fabrics appeared to have electrical connections at the wire crossings while, at other areas, the wire crossings may have been insulated by resin. The shielding effectiveness of coatings that indicated good wire-to-wire contact were not greatly affected by the penetration discharges except for possibly a slight degradation at the arc attachment point due to the breaking of wires. On the other hand, the shielding effectiveness of coatings that indicated poor wire-to-wire contact was improved by the penetration discharges since the current pulse created more wire-to-wire contact. The same effect was also noted in the aluminized-glass-coated panels.

Table 2 gives the shielding effectiveness before and after the penetration tests at 0.2 and 4.0 MHz. The shielding effectiveness measurements taken after the penetration tests were conducted at two locations, one directly over the arc attachment point and the other over an area where the fusing current of the penetration discharge caused the maximum shielding effectiveness.

4.4 ANTENNA GROUND PLANE REQUIREMENTS

Some applications of composite materials may require that the coating system act as the ground plane of an antenna system. It is therefore necessary to consider the effect a coating system would have on the antenna properties when it is the ground plane.

The resistive losses in the ground plane of an antenna adds to the total impedance of the antenna and, thereby, lowers its efficiency. If the power loss in the ground plane is excessive,

Table 2. Shielding Effectiveness Before and After Electromagnetic Penetration Tests (dB)

Panel	At 0.2 MHz			At 4.0 MHz		
	Before discharges were applied	After discharges were applied		Before discharges were applied	After discharges were applied	
		Measured at arc attachment point	Measured at maximum shielding area		Measured at arc attachment point	Measured at maximum shielding area
500-BR28-AR08X-FG04	8	9	11	28	22	32
509-GP96-AR04Z-0000	3	6.5	8	17	21	27
510-GP97-AR08X-0000	13	12	13	39	35	39
511-GP98-AI05N-0000	2	5	8	15	20.5	30
512-BR32-AR04Z-0000	8	6.5	10	29	23	32
513-BR33-AR08X-0000	2	9	13	7	28	30
514-BR34-AI05N-0000	3	6	7	9.5	20	28

the heat generated could cause degradation to the coating system. In general, the resistive losses in an antenna assembly lowers the Q of the antenna and makes the impedance matching problem simpler—naturally with an associated loss of efficiency. Reradiation interference due to excitation of inhomogeneous or discontinuous ground planes need not be considered since the discontinuities in the coating systems recommended herein (i.e., fabrics and meshes) are very small compared to a wavelength at the highest frequencies considered.

The losses in an antenna system due to a ground plane constructed of resistive material is first examined by using a quarter-wave monopole as an example of an electrically long antenna. Current flowing radially outward from the base of the antenna on the ground plane is equal to the current into the base of the monopole. The current density decreases rapidly as the distance from the base of the monopole antenna increases. Therefore, the maximum current density and, hence, the maximum loss due to I^2R heating occurs adjacent to the monopole. The radius of the base mount will be a factor in the losses of the antenna system since larger base mounts eliminate heating losses in the coating material replaced by the mount.

At frequencies above 10 MHz, the skin depth is less than the thickness of the proposed coating systems and contains more than enough aluminum to make an adequate ground plane. Contact to the surfaces of the woven wire coatings is accomplished easily by removing the surface resin with light sanding and making a faying surface contact. The aluminized glass fiber coating will require more care in obtaining a good contact with the antenna system since layers running perpendicular to each other are isolated by resin. Extra effort will be required to ensure that the antenna ground contacts at least the outer two layers of aluminized glass.

At lower frequencies, the recommended coating systems may not provide adequate conduction for many typical transmitting antenna installations. This will be especially true when the notch techniques employed require high-current densities at and around the antenna feed point. These antennas are often limited by their efficiencies, and additional losses due to a coating system with a thickness less than that of the skin depth would result in unacceptable losses. This type of antenna on a composite structure would perhaps require a copper or aluminum inlay in areas of high current concentration.

4.5 ELECTRICAL SYSTEM GROUND RETURN

The ground return for an electrical system must have a current-carrying capacity equal to that of the feeder system. As an example, consider an aluminum wire AWG size 8 with a current-carrying capability of 60 A in free air (based on MIL-W-5088). This wire has a cross section of 16,510 circular mils. An equivalent cross section of coating would be required if this wire was used to feed a system that used the coating as the ground return. Coating AR04Z, using 2-mil wire with 200 wires per inch, has a cross-section area of 800 circular mils per linear inch; therefore, a grounding lug with a circumference of nearly 21 in. would be required.

5.0 LIGHTNING TEST RESULTS

Tests of coated composite panels are of two types: high-current tests and high-coulomb tests. Information on each test performed is given in abstracted form in appendix Tables A-1 and A-2. The test pulse employed for high-current testing nominally reached the peak value in 11 to 12 μs and had a duration at 22 to 24 μs as shown in Figure 6.

The tensile strength tests are summarized in table A-4. Each laminate, identified by its three-digit code number, was cut into 10 or 11 coupons 0.5 in. wide, as described in Figure 1. The specimen suffixes (1 through 10 or 11) are sequential from left to right looking at the coated surface of the panel. Therefore, specimens with suffixes 5 and 6 represent those taken from the center of the panel where the simulated lightning discharge was directed. These are the specimens that would be expected to be damaged the most. Specimens 1 and 10 or 11, taken from the edges of the panel farthest from the electrical discharge, would be expected to be damaged the least.

5.1 HIGH-CURRENT TESTS

Unprotected boron-filament- and graphite-fiber-reinforced plastics are severely damaged by high-current flow through the reinforcement. In boron-filament-reinforced plastics, the current causes the filaments to crack and break. This can result in the total loss of useful mechanical strength. Peak currents as low as 40 kA have totally destroyed the strength and rigidity of 6- by 12-in., five-ply laminates. Larger laminates may not be totally destroyed at this current level but suffer significant reductions in strength. In graphite-fiber-reinforced plastics, Joule heating of the fiber causes resin pyrolysis and, eventually, fiber destruction by a mechanical whipping action (Ref. 7). The damage is less widespread than that of comparable boron composites, however. In both composites, the damage is not limited to the arc contact zone but travels toward electrical ground.

In contrast to these reinforced plastics, metal structure of comparable strength and stiffness is not so susceptible to damage by high-current discharges. Typical results of these tests are zones of melted metal at the arc contact point. The damage generally does not extend beyond this zone. Metal foils are thus a logical protective coating for boron-filament- or graphite-fiber-reinforced plastics. Typically, high-current tests of thick aluminum foil coated plastics causes an area of the foil to be vaporized, but no damage to the reinforced plastic. Thin foils, i.e., five mils or less, are less satisfactory because scorching of the resin matrix and current penetration into the reinforcing fibers or filaments can occur.

Since boron-filament-reinforced plastics may undergo severe mechanical damage due to high-current flow through the filaments with little or no visible damage to the composite, it is necessary to measure residual mechanical properties to fully evaluate the coating effectiveness. Such tests have found 6-mil-thick aluminum foil to fully protect both boron-filament- and graphite-fiber-reinforced plastics from discharges as high as 194 kA. Damage to the foil consists of a small vaporized area centered in a larger area of foil that has been melted. The residual tensile strength directly under the vaporized spot is the same as that of the remainder of the composite. The residual tensile modulus of the boron-filament-reinforced laminate was lowest at the spot location, but it was within the standard deviation of all the points for that

laminate (panel 472). Thin aluminum foils, e.g., 1 to 3 mils thick, can protect comparable laminates from lesser discharge levels but not from 200-kA peak current levels. Overcoatings of paint impair coating performance. Six-mil-thick aluminum foils topcoated with an acrylic paint appear to concentrate the damage in a small area. Examination of the composite under this area indicates minor damage at that point. This phenomenon was more clearly illustrated in the study of metal fabric coatings.

Metal wire fabrics have been found to provide excellent protection from simulated high-current lightning tests (Ref. 1). The fabrics possess the hand and drape necessary for use as an overlay on complex contoured parts. Additionally, the composite matrix fully encapsulates the fabric and protects it from the environment. A wide range of tests have found aluminum wire fabrics very resistant to environmental exposures including prolonged (90-day) salt spray; 30-day immersion in jet fuel, hydraulic fluid, or boiling water; Weather-O-Meter testing (FED-STD-141, method 6152); or prolonged exposure to hot, humid (140° F, 100% relative humidity) conditions. Environmentally exposed laminates were found to be unchanged when compared with unexposed controls and performed equally well when subject to high-current discharge. In this regard, these coatings outperform others since most other coatings are susceptible to corrosion as determined by salt spray exposure. This is particularly true of unprotected metal foils which suffer extreme corrosion. Resin encapsulated wire fabrics are protected from the corrosive action of this environment by the resin. Since bare metal is not exposed to the environment, corrosion is retarded.

Aluminum wire fabrics are the lightest, state-of-the-art lightning protective coatings. For 200 by 200 mesh woven aluminum wire fabric, the area density is 0.019 lb/sq ft. A 120 by 120 mesh fabric has an area density of 0.042 lb/sq ft. These weights are increased to 0.036 and 0.072 lb/sq ft, respectively, if one accounts for the resin required for encapsulation of the fabric. Some weight saving is possible by employing calendered wire cloth. This serves to reduce the thickness of the cloth by flattening the intersections of the wires. Weight savings occur because less resin is required to encapsulate the flattened mesh. As a point of reference, 6-mil-thick aluminum foil has an area weight of 0.084 lb/sq ft. The weights of environmentally protective topcoats or adhesive required for bonding the foil (or fabric) must be added to these figures.

The outstanding performance of wire fabrics as lightning protective coatings is due to their use of the skin effect for electrical conduction. The skin area of a 200 by 200 mesh wire fabric, using a 0.0021-in.-diameter wire, is over 200 times that of the area actually coated by the fabrics. Consequently, the fabric is highly efficient in conducting electricity away from the arc contact zone. This fabric has been found capable of withstanding successive 100-kA discharges at the same location with little visible damage to the fabric and no reduction in the mechanical strength of the coated laminate (panel 427). At the 200-kA level, some damage to the coated boron laminate is detectable. The residual tensile strength of coupons taken directly under the arc contact zone is typically only 80% of the panel average (panel BR5, Fig. 21). The residual tensile strengths of graphite-fiber-reinforced coupons at the damage zone were 85%, 84%, 71% and 89% of the undamaged values. Of these, only the lowest was statistically significant.

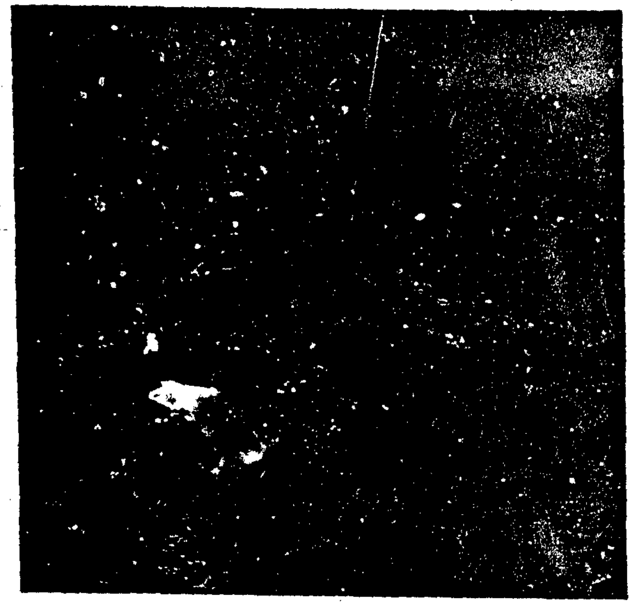


Figure 21. Boron-Filament-Reinforced Epoxy Laminate Coated With 200 by 200 Mesh Aluminum Wire Fabric After Exposure to 200 kA

This coating system can be improved by incorporating a single ply of a glass fabric between the coating and the composite. In the case studied, one ply of style 120 glass fabric prevented mechanical damage of the boron-filament-reinforced laminate, although the graphite-fiber-reinforced laminate was damaged at the arc contact zone (panels 498 and 389, respectively). Damage to the graphite laminate was restricted to a 1/2-in.-wide zone. The tensile test coupons adjacent to this location maintained their full, unexposed tensile strength.

Overlays of paint are deleterious to lightning protective coatings. The paint confines the electrical energy to a smaller surface area permitting a greater amount of electrical energy to penetrate into the composite. At the 100-kA test current level, this is evidenced by an increase in the amount of damage to the coating, i.e., a greater amount of wire is vaporized or melted. However, composite residual tensile strengths are unchanged, indicating excellent coating performance (panel 454). At the 200-kA test current level, the damage is more severe. With graphite-fiber-reinforced composites, damage at the arc contact zone is visible as exposed resin-free graphite fibers. These are visible in Figure 22. Three different tests of two different laminates (panels 458 and GR5C) have found the damage limited to the 1/2- to 1-in.-wide arc contact zone. With boron-filament-reinforced laminates, the residual tensile strength at the arc contact zone is only 20% of the control value, while those 1/2 in. to either side of this point were but 50% of the control. The residual strength returns to the control value within the next half inch. Consequently, the damage zone is limited to a 1-1/2- to 2-in.-wide area for boron laminates (panel BR5C).

Figure 22. Painted Graphite-Fiber-Reinforced Epoxy Laminate Coated With 200 x 200 Mesh Aluminum Wire Fabric After Exposure to 190 kA

Heavier, 120 by 120 mesh aluminum wire fabric also provides an excellent level of lightning protection. Residual mechanical properties indicate no loss of strength due to high-current exposure subsequent to prolonged salt spray exposure. Additionally, exposure to 180- to 200-kA test current levels prevented damage at the arc contact zone. In the case of panel 452, collision of the discharge probe with the laminate during test caused extensive damage. This was borne out by subsequent mechanical testing. Panel 453 was also damaged mechanically but only at the collision point. In this case, the arc contact zone maintained 50% of the control tensile strength. Since the test coupon had a preexisting, 1/4-in.-long crack, it can be concluded that little electrical damage was introduced into the composite.

Both painted and unpainted graphite-fiber-reinforced laminates coated with this fabric were damaged at the arc contact area. Residual tensile strengths were only 10-20,000 psi in this region, compared with 70-75,000 psi control values. This damage was confined to a 1/2-in.-wide zone of the composite and was due to resin pyrolysis. It must be concluded that current penetration into the reinforcing fibers was not totally prevented.

The concept of electrically conductive coatings using fine wires as the current-carrying member has been extended through the use of aluminized glass. Unidirectional layers consisting of several thousand conducting members per lineal inch can be fabricated using current filament winding technology. Model studies used copper wires as the conductive filament. These studies found it necessary to use at least two orthogonal layers to provide good lightning protection (panels 391-399, 407-410). The fact that the wires were electrically insulated from one another did not prevent the coatings from performing satisfactorily. These findings were confirmed with aluminized glass coatings.

Optimum coatings of aluminized glass used two layers of fibers. The fibers in each layer were aligned in one direction only, and it is necessary that the fibers in one layer be orthogonal to those of the other layer. Excellent results were obtained with coatings containing 4500 aluminized filaments per lineal inch per ply. Two-ply coatings satisfactorily protected boron-filament-reinforced composites from current levels as high as 180- to 190 kA (panel 478). None of the coupons cut near the arc contact zone had lost mechanical strength or stiffness. Four plies of filaments performed equally well with boron-filament-reinforced composites and were required to completely protect graphite-fiber-reinforced composites where two-ply coatings worked well but did not prevent some loss of tensile strength at the arc contact zone. For example, the contact zone had a tensile strength of 14 ksi in panel 505, while the remainder of the panel averaged 59 ksi. Some typical results with this type of coating are shown in Figure 23.

Aluminized glass filaments provide excellent high-current protection for boron-filament-reinforced plastics. Coating area weights of 0.040 lb/sq ft (including resin) are easily prepared and handled. This coating is less satisfactory for graphite-fiber-reinforced plastics since a heavier (0.080 lb/sq ft) coating weight appears to be required. Corrosion may be a problem with this aluminum-carbon galvanic couple since panels exposed to a 3% salt spray for 30 days underwent severe corrosion especially about the edges. Coatings applied to boron-fiber-reinforced laminates did not undergo corrosion when exposed to similar conditions. These differences are illustrated in Figure 24.

Additional tests have shown that aluminized-glass-fiber coatings can protect honeycomb sandwich panels from extensive damage by high-current discharges. At the 100-kA test level, no damage to either boron-filament-reinforced or graphite-fiber-reinforced face sheets was discernible. At the 200-kA test level, the five-ply face sheets were punctured and damaged in 3/4- by 3/4-in. areas. Sections of the panels taken from the damaged area indicated no damage to the aluminum honeycomb core except at the puncture, where the core was crushed. No evidence of electrical burning damage was found in either the honeycomb core or the face sheets. Microscopic investigation of the face sheet cross section found only mechanical damage at the puncture. Apparently the conductive coating and the conductive core prevented excessive current levels from penetrating into the reinforcing fibers or filaments.

These high-current tests and the residual tensile properties of exposed laminates have shown that excellent lightning protection systems can be based on continuous-metal foils, metal wire fabrics, and metallized glass fibers. Other developmental coatings have been sought, but, of these, only sprayed metal has promise (Ref. 1). Continued investigations of silver-pigmented paints has failed to find a system that performs satisfactorily. Excessive coating thicknesses were required to prevent damage to the substrates, even at the 100- to 120-kA test level. A 6-mil-thick coating with a weight of 0.09 lb/sq ft is required to prevent serious damage to boron-filament-reinforced laminates when exposed to a 99-kA test current (panel 309). Significant coating damage occurs even when this thickness is increased to 12 mils (panel 308) or when an insulating polyimide film underlayer is provided (panel 324). No protection was afforded to graphite-fiber-reinforced laminates unless the dielectric underlayer was provided. Replacement of the 1-mil-thick polyimide film with a 2-mil-thick, sprayable, polyurethane circuit board coating only enhanced damage to the substrates (panels 363 and 375). While these results varied somewhat depending upon the source of the actual materials used, the best performing silver-pigmented paint studied (Hysol K9-4239) is very heavy

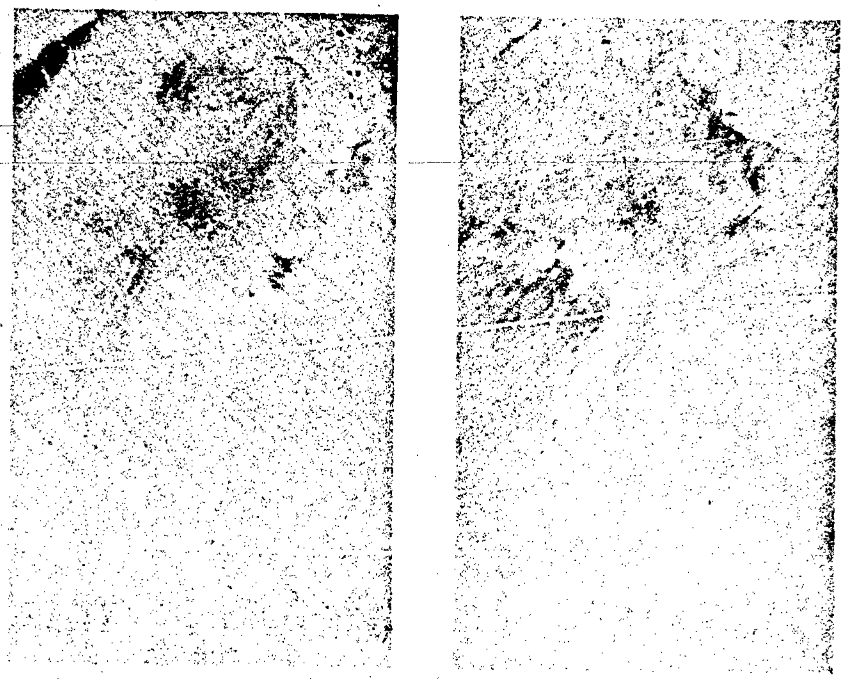


Figure 23. Aluminized, Glass-Coated, Graphite-Epoxy Laminates After Exposure to High-Current Tests

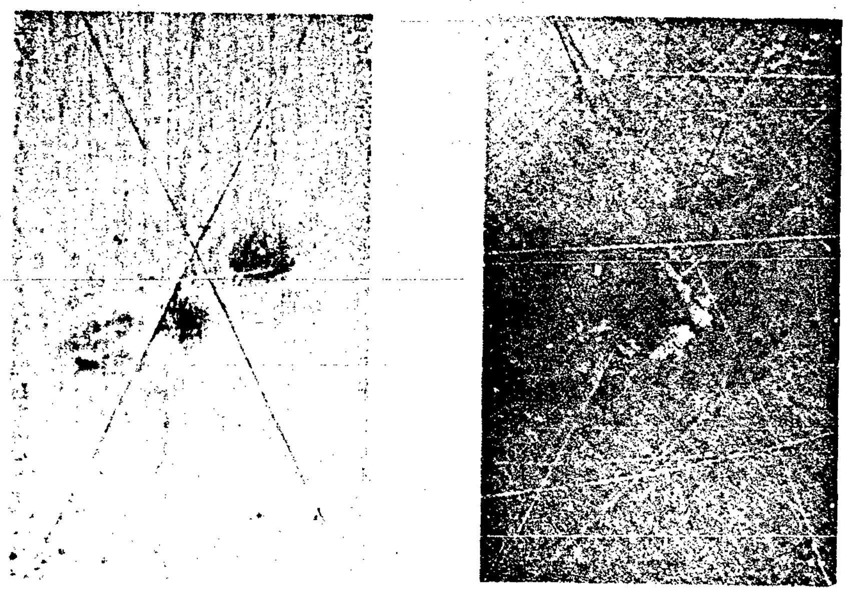


Figure 24. Aluminized, Glass-Coated, Graphite-Epoxy (left) and Boron-Epoxy (right) Laminates After Exposure to 3% Salt Spray for 30 Days; Graphite-Epoxy Laminate Displays Coating Corrosion

compared with coatings using continuous-metal conductors. Furthermore, the poor results obtained at moderate current levels make it highly improbable that any of the systems studied would perform well at the 200-kA test level without imposing a serious weight penalty.

Other coatings in developmental stages have similar defects. Chopped metal fibers can be incorporated into a satisfactory but heavy coating. Dielectric coatings have performed well only when polyimide film underlayers were provided. Such underlayers present serious fabrication problems. In addition, these dielectric coatings also require metal strips to conduct the current to electrical ground and must be pin-hole free to prevent arcing to the reinforcing fibers. Such problems are not easily resolved.

5.2 HIGH-COULOMB TESTS

High-coulomb tests involve long-duration, high-temperature areas that can cause severe burning damage, although this type of damage is frequently quite localized. Nevertheless, no coating can withstand an extremely high coulomb test when the arc is confined to a small surface area. The coatings burn away almost immediately, and the arc will attach itself to the conductive panel. Damage then propagates toward electrical ground.

In a series of tests designed to illustrate this phenomenon, several 0.080-in.-thick aluminum plates were subjected to high-coulomb tests. It was found that a 209-C transfer could melt a 3/4-in.-diameter zone of the plate. Tests at lower coulomb levels indicate that the volume of metal melted is directly proportional to the level of coulombs transferred. The type of damage observed with metal plate is also dependent upon the current-time parameters employed. A series of tests at the 100-C transfer level illustrate this point. Low-amperage (23.3 A), long-time (4.35 sec) arcs cause only flash marks on the metal surface. Conversely, high-amperage (392 A), short-time (0.25 sec) arcs melt a 1/2-in.-diameter hole through the plate. Intermediate-amperage (87 A), intermediate-time (1.16 sec) arcs melt areas through the plate but do not cause holes to be formed. These results illustrate Joule heating damage. The heat in calories developed in a circuit by an electrical current is proportional to the square of the current but only linear with time.

For the constant-coulomb transfer tests described above, and assuming constant electrical resistance, the ratios of the heat developed would be 1:4:16, the last representing the high-current, short-time test. In view of these results, it is apparent that a protective coating of reasonable thickness will prevent damage to the substrate only if the discharge is a moderate number of amperes or if the electric arc is forced to dissipate its energy over a large surface. This might occur in the zone II and III regions of an aircraft where the lightning stroke is swept along the surface by the flow of air (Ref. 4). Areas of the aircraft where the stroke continues to make contact with the same point, such as appears to be the case with trailing edge attachments (Ref. 8), will not be as well protected.

In view of the above, it is not surprising that metal-foil-coated plastics are damaged by high-coulomb discharges. Six-mil-thick aluminum foil was burned away and a 1/2-in.-diameter hole burned through the boron-filament-reinforced laminates. The residual tensile strengths indicate no strength at all in a 1-in.-diameter zone. The next 1/2 in. was only 30% of undamaged strength, and the remainder of the laminate was undamaged (panel 474).

The graphite-fiber-reinforced laminate was less extensively damaged. The discharge destroyed a 1-1/8-in.-diameter area of the outer ply of fibers, lesser amounts of the next two plies, but pyrolyzed the resin in the remaining plies. The damage zone had no residual strength, while one of the adjacent coupons appears undamaged. The other coupon was 38% of the undamaged panel average. Overcoatings of paint lessened coating performance, as nearly comparable, i.e., 1-1/2-in.-diameter damage zones were observed at only half the coulomb transfer level (panels 360 and 374).

High-coulomb tests of wire-fabric-coated laminates yielded two types of results: those in which the arc attached at only one point on the surface and those where it did not. In the latter instances, little or no damage to the substrates was observed. The "wandering" of the arc was unpredictable but occurred most frequently with coated boron-filament-reinforced plastics. Coulomb transfers as high as 140 C were achieved (panel 457). A coating of 200 by 200 mesh aluminum wire fabric with an underlayer of epoxy-resin-impregnated, style 120, glass fabric produced arc wandering at a test level of 232 C. The result for boron is shown in Figure 25. Residual tensile tests of this laminate (panel 499) found no damage, nor was damage observed when the substrate was graphite (panel 389, coulomb transfer 176 C). The average tensile strength was 40,300 psi. The lower-than-normal average tensile strength was due to misorienting the fibers of the laminate; only two of six plies were in the 0° direction. The presence of the glass fabric insulating layer greatly improved the performance of this coating system.

When the arc did not wander on the coating surface, burning damage to the coating and the composite substrate occurred. Furthermore, the damage to five-ply boron laminates appears to be linear with the number of coulombs transferred. Figure 26 shows the relationship between the size of the hole and the test level in coulombs for 200 by 200 mesh, aluminum wire fabric coated, boron-filament-reinforced laminates. The area damaged increases linearly with an increase in the test level. Residual mechanical properties of the laminates indicate the damage was restricted to the visible burn areas. Generally, the boundaries of the burn zone were quite sharp.

That localized damage does occur with high-coulomb tests was proven with flexural strength tests of two 14-ply laminates coated with 200 by 200 mesh aluminum wire fabric. The data are given in Table 3. For these tests, the laminates were cut into five 1-in.-wide strips, labeled -1 to -5 such that -1 and -5 were the edge strips, -3 was the center, etc. Each strip was then cut into two parts with the parts nearest electrical ground labeled -6 through -10. Thus, -3 and -8 were cut from the center, -5 and -10 from the right edge, etc. The coupons were tested per ASTM D790, with a 32-to-1 span-to-depth ratio.

The test data show reduction of strength in the graphite-fiber-reinforced laminate only at the burn center. Even between the burn center and electrical ground no damage was detectable. The boron-filament-reinforced laminate was undamaged as the arc wandered across the surface, burning the coating of all specimens except -6 and -7.

Very similar behavior was observed with aluminized, glass-fiber-coated laminates. If the arc wandered, little or no damage occurred. If the arc attached to the reinforcing filaments, severe damage occurred. A 200-C transfer test to a two-ply coating (4960 conductive filaments per inch) burned a 1-in.-diameter hole through the boron-filament-reinforced laminate and caused mechanical damage in a 2-1/2-in.-diameter area. Yet, a 180-C transfer test to a

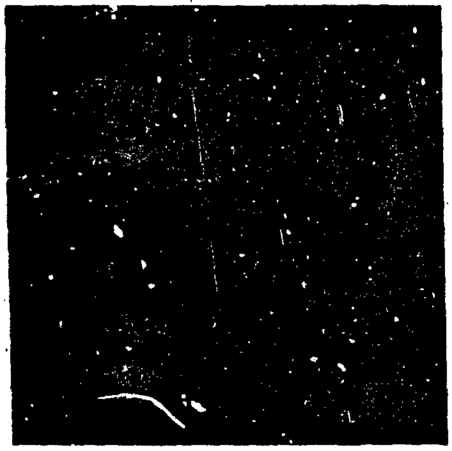


Figure 25. Aluminum-Wire-Fabric-Coated, Boron-Filament-Reinforced Epoxy After Exposure to 232 C

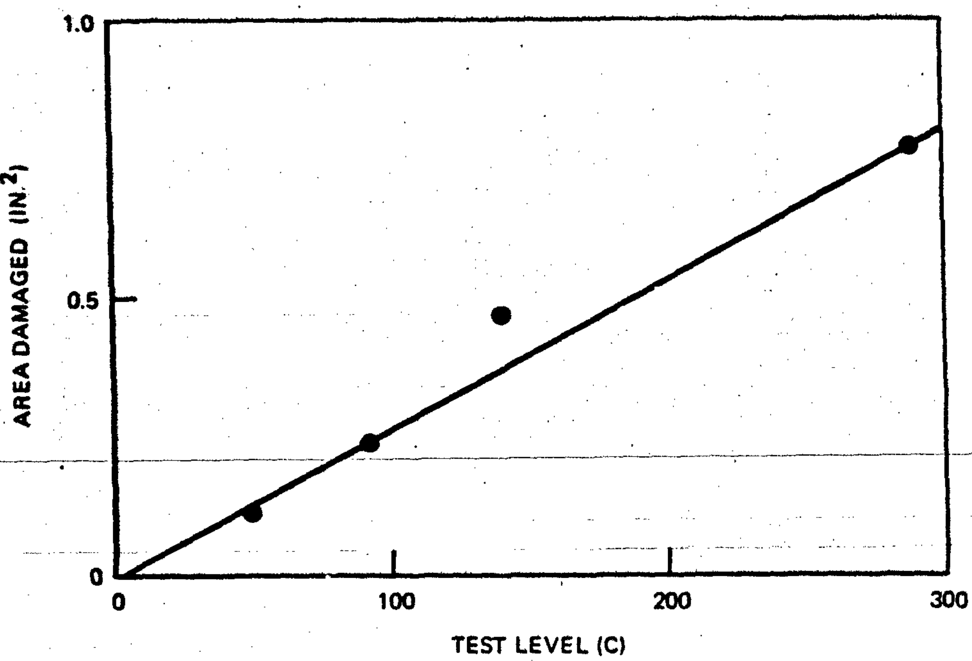


Figure 26. Damage Versus Coulombs Transferred for 200 by 200 Mesh, Aluminum-Wire-Fabric-Coated, Boron-Filament-Reinforced Laminates

Table 3. Residual Flexural Properties of Aluminum-Fabric-Coated Laminates

Boron reinforcement (140-C test level)			Graphite reinforcement (206-C test level)		
Specimen	Flexural strength (ksi)	Flexural modulus (psi x 10^6)	Specimen	Flexural strength (ksi)	Flexural modulus (psi x 10^6)
323-1*	88.2	11.3	446-1	63.4	13.7
-2*	97.8	12.7	-2	64.3	13.8
-3*	87.9	11.6	-3*	43.3	11.5
-4*	97.1	11.6	-4	69.7	14.1
-5*	93.1	11.7	-5	64.8	13.5
-6	87.5	11.8	-6	60.5	13.6
-7	93.0	12.1	-7	64.7	14.1
-8*	82.6	11.1	-8	59.8	14.0
-9*	91.1	12.1	-9	62.2	14.2
-10*	87.9	11.8	-10	68.8	14.4
Avg	90.6	11.8	Avg	62.2	13.7

*Visible damage to coating

similarly coated graphite-fiber-reinforced laminate (panel 506) caused no damage as the arc wandered on the panel surface. This series of tests indicates that localized damage caused by the high-coulomb component of the lightning stroke will occur unless the arc wanders or sweeps across the test surface.

5.3 BOEING-McDONNELL DOUGLAS LIGHTNING TESTS

A series of special laminates were coated with 200 by 200 mesh, aluminum wire fabric and subjected to separate lightning tests by Boeing and McDonnell Douglas (Ref. 9). Both painted and unpainted 12- by 12-in. laminates were tested. The lettering code is:

BR = boron-filament-reinforced epoxy

GR = graphite-fiber-reinforced epoxy

5 = five plies

14 = fourteen plies

C = painted

The laminates were tested in one quadrant by McDonnell Douglas, returned to Boeing, and tested in the diagonally opposite quadrant. The waveforms for these tests were very similar to those shown in Figure 8, i.e., the high-current peak value was reached within 12 μs and the pulse duration was 24 μs. When the test included a high-coulomb discharge, the long-duration arc was established during the high-current test and continued after the initial high-current discharge was complete. After simulated lightning testing, the residual tensile properties of the laminates were determined. These data are presented in appendix Table A-5. The laminates were oriented such that the first quadrant tested fell in the region of coupons 1-11; the second (Boeing test) quadrant fell in the range of coupons 12-22.

The data for the high-current tests are given in Table 4, and the panels are shown in Figure 27. Visually the panels appear damaged equally by each of the two discharges. In fact, the measured damaged areas of the coating were only slightly larger for the McDonnell Douglas tests. The graphite-fiber-reinforced laminates also displayed more evidence of resin pyrolysis. This is probably due to the larger coulomb values for the McDonnell Douglas tests

Table 4. High-Current Test Parameters

Panel	McDonnell Douglas		Boeing	
	Peak current (kA)	Coulombs transferred	Peak current (kA)	Coulombs transferred
BR5	200	3.80	194	2.35
BR5C	184	3.65	184	2.26
GR5	170	3.60	194	2.42
GR5C	180	3.70	189	2.40

(Table 4). The uncoated graphite laminate displayed no loss of mechanical properties after either test. The painted graphite laminate was less damaged by the Boeing test, reflecting the observed difference in resin scorching. The paint on this panel was 4 mils thick. No distinction between the two test facilities was observed with the boron-filament-reinforced laminates. However, the painted boron-filament-reinforced panel was much more severely damaged than the unpainted panel. The residual tensile strength of the painted panel at the damage zones fell to approximately 25% of original strength; the unpainted laminate maintained 75% of original strength at the damage center. The paint on this panel was 7 mils thick.

High-coulomb tests were directed at thicker, 14-ply laminates. The pertinent test data are given in Table 5. The panels are shown in Figure 28.

Table 5. High-Coulomb Test Parameters

Panel	McDonnell Douglas		Boeing	
	Initiation peak current (kA)	Coulombs transferred	Initiation peak current (kA)	Coulombs transferred
BR14	213 —	— 190	213 84	33 174
BR14C	200	136	217 88	30 196
GR14	216	310	217 80	75 206
GR14C	209	920	220	230

Panel BR14 was extensively damaged by the McDonnell Douglas test, and a 1/2-in.-diameter hole was burned in the panel. The first Boeing test was a 33-C transfer with no panel damage. A second test (174-C transfer) caused extensive panel damage over a 3/4-in.-wide, 10-in.-long section. Panel BR14C was also punctured by the McDonnell Douglas test. A 30-C test by Boeing caused no damage, but a 196-C transfer burned a 1/4-in.-diameter hole through the panel. Visible damage from both discharges extended 2 in. beyond the holes.

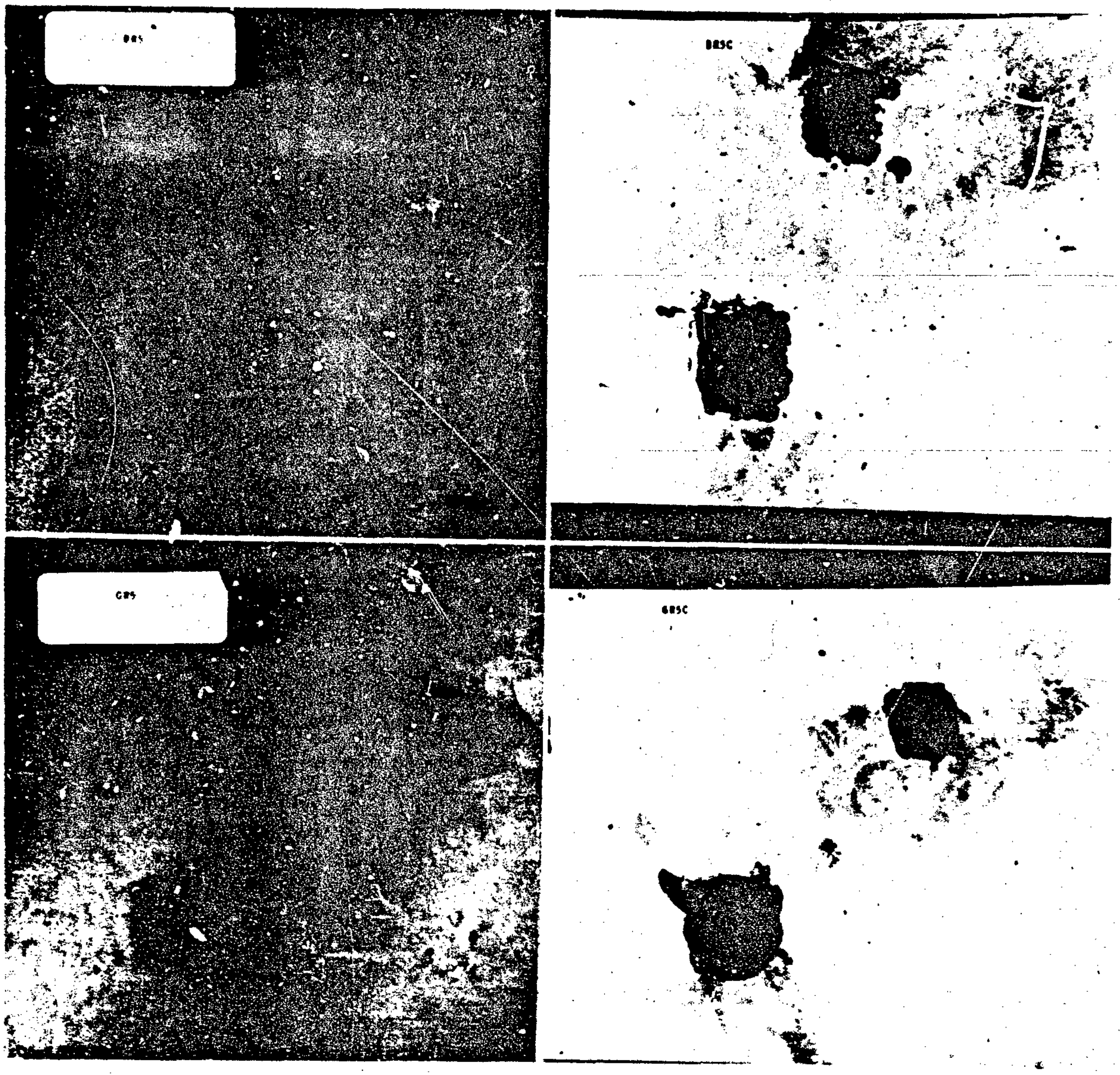


Figure 27. Boeing-McDonnell Douglas Test Panels After High-Current Testing

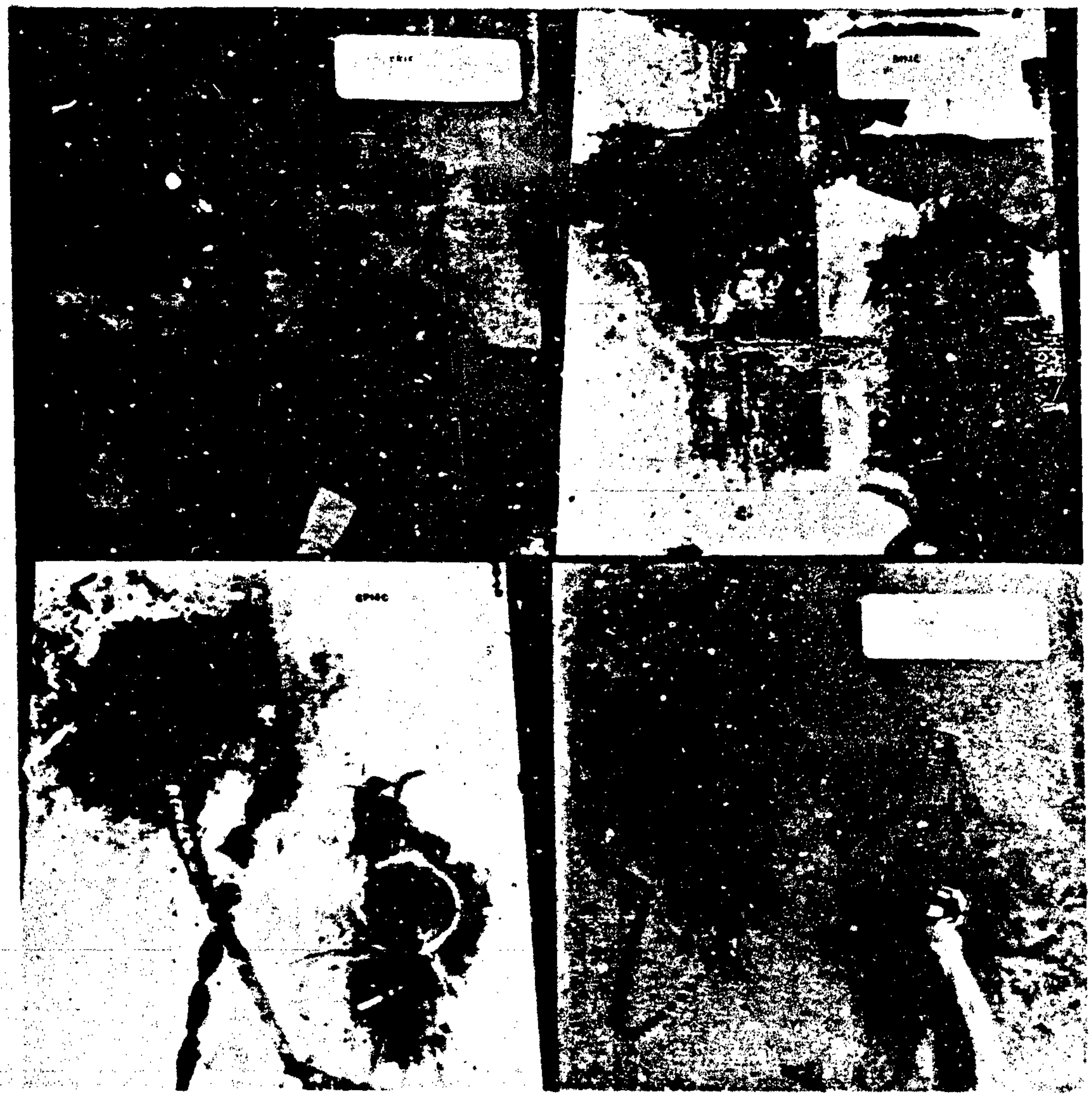


Figure 28. Boeing-McDonnell Douglas Test Panels After High-Coulomb Testing

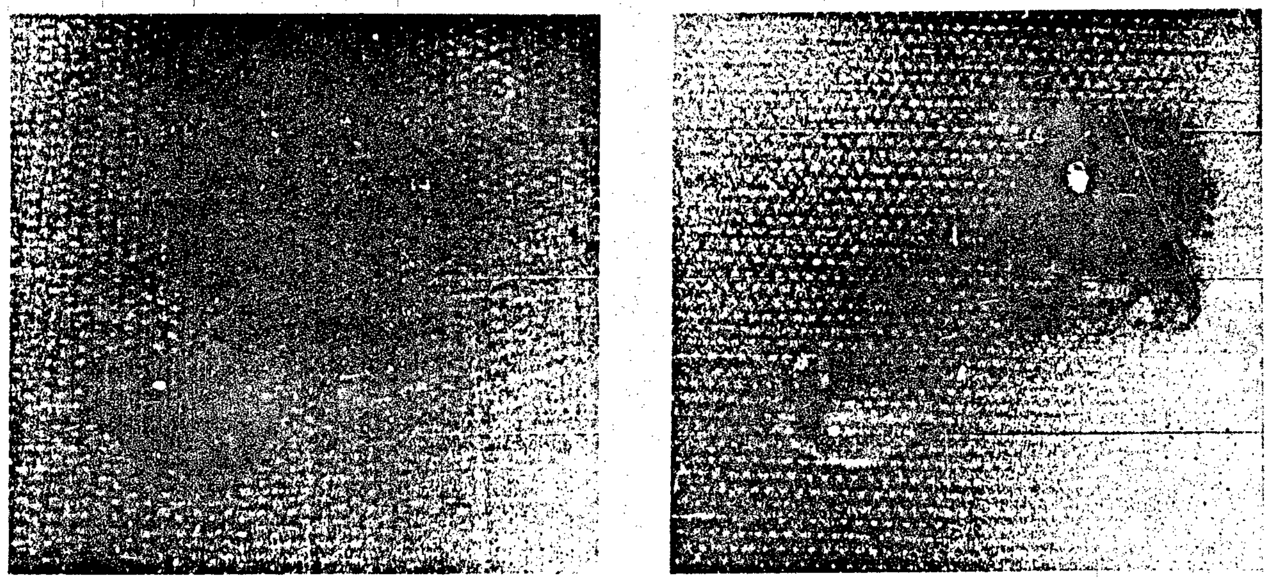


Figure 29. Backside Damage to Panels BR14 (Left) and BR 14C (Right)

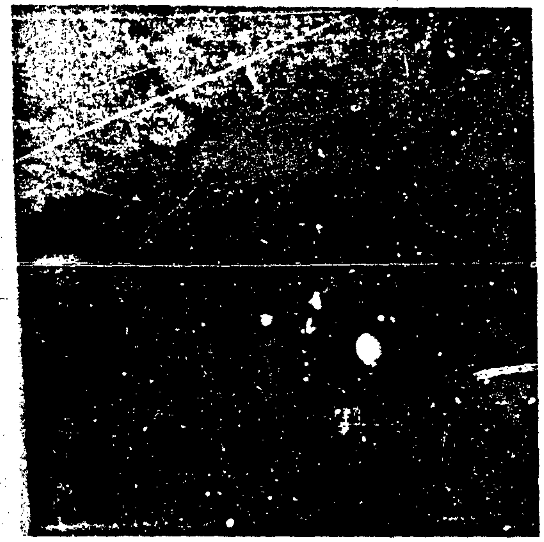


Figure 30. Damage to Panel BR14 Prior to Boeing Tests

Backside damage to these panels is shown in Figure 29. It can be seen that the hot-spot zones were considerably larger than the holes. Additionally, the repeated testing of the laminates appeared to enhance the damage in the already weakened areas.

Figure 30 illustrates the edge damage near the hole of panel BR14 before the Boeing tests. This same area was pitted and burned after these tests (see Fig. 29). Mechanical testing showed the damage to be 2-1/2 in. wide at the Boeing test zone but more extensive (3-1/2 to 6 in.) at the McDonnell Douglas test zone. The greater damage at the latter location is due in part to the Boeing tests.

Tensile tests of the painted laminates indicate 2-in.-wide damaged areas at each test zone. Damage did propagate from the arc attachment point to electrical ground. The damage appeared to skip a portion of the panel and burn a zone near the center of the panel as well.

The graphite-fiber-reinforced panels were less extensively damaged than the boron-filament-reinforced panels. Panel GP14 maintained 50% of its original tensile strength at the center of the burns. The damage at each burn was limited to two tensile coupons or about 1 in. in width. Damage to GP14C included three tensile coupons or about 1-1/2 in. of panel width. Even at the center of the 920-C discharge, the laminate had a residual tensile strength of 21,000 psi. Differences between residual tensile strengths were as expected due to the different test levels applied to the graphite-fiber-reinforced laminates.

6.0 CONCLUSIONS

1) Electric current flow in boron-filament- and graphite-fiber-reinforced plastic composites can cause catastrophic damage. This damage is due to filament breakage or cracking in the case of boron but mostly resin pyrolysis and attendant explosive delamination with graphite.

2) Several lightweight coatings can protect the composites from the high-current component of an artificial lightning stroke. These coatings are: 6-mil-thick aluminum foil, 200 by 200 mesh aluminum wire fabric, 120 by 120 mesh aluminum wire fabric, and a coating containing aluminized glass filaments. These coatings can withstand restrikes at the 100-kA test level with no coating repair required. At the 200-kA test level, the 200 by 200 mesh fabric allowed limited damage to the boron composites while the other coatings did not. Only the metal foil coating prevented damage to graphite composites at this test level.

3) Overlays of paint were deleterious to the performance of all coatings. Damage to the composites occurred at the 200-kA test level. Aluminum foil and 200 by 200 mesh wire fabric were the better performing systems under this test condition.

4) The wire fabric coatings were resistant to normal aircraft environments. Corrosion, as determined by 3% salt spray, was the least with these coatings. Metal foils had poor resistance to salt spray. Aluminized glass coatings performed poorly on graphite composites, although little corrosion occurred on boron composites.

5) None of the coatings fully protected the composites from high-coulomb damage. Some tests with wire-fabric and aluminized-glass coatings resulted in the arc wandering on the coating surface. When this occurred, no damage to the composite was observed.

6) The damage induced in test laminates by the two different test facilities appears comparable for comparable test levels. Existing damage areas appear to be further damaged by successive simulated lightning tests, even when the additional discharges are directed to undamaged portions of the test panel.

7) The wire-fabric, metal-foil, and aluminized-glass coatings have no triboelectric charging tendencies unless covered with a dielectric material. The coatings have little electromagnetic shielding effectiveness.

APPENDIX
TEST PANEL SUMMARY

A numbering system is employed for test panel identification and retrieval. The system consists of sixteen characters in four fields:

XXX-XXXX-XXXXX-XXXX

The fields designate the test serial number, the panel identification, the coating description, and the undercoating identification, respectively. An optional fifth field indicates environmental exposure prior to test.

The first field is a three-digit number unique to each simulated lightning discharge, e.g., 184.

The second field consists of two letters followed by two digits. The letters describe the nature of the panel substrate, while the digits serialize the particular substrate, e.g., BR01 refers to the first boron-filament-reinforced epoxy laminate.

The third field, the coating description, utilizes five characters. The first two are letters which designate the coating, e.g., AF designates aluminum foil. Next, two digits give the total thickness in mils of the coating. This number does not include the undercoating in the thickness calculation. The last character is a letter which describes particulars of the coating, such as the mesh count for a fabric or the degree of surface coverage by a foil. Thus, the designation AF01C represents an aluminum foil coating, 1 mil thick, which provides complete surface coverage to one exposed face of the substrate.

The fourth field characterizes the undercoating. The two letters designate the undercoating and are followed by two digits which give the thickness in mils. For example, KF01 designates Kapton film 1 mil thick.

Two additional characters have been added to this numbering system to indicate exposure to hostile environments prior to lightning test. These characters follow the fourth field and are preceded by a slash.

The characters used in the numbering system are defined in Table A-1. Table A-2 summarizes the panels examined. The panels are numbered from 292 to avoid confusion with panels described in reference 1. Tables A-3 and A-4 summarize the tensile test results. Table A-5 summarizes the Boeing–McDonnell Douglas test panels.

Table A-1. Panel Identification Code

First Field: Test Serial Number
A three-digit number unique to each lightning discharge

Second Field: Panel Composition

AL	–	Aluminum sheet
BR	–	Boron-filament-reinforced epoxy
GP	–	Graphite-fiber-reinforced epoxy
FG	–	Style 181 glass-fabric-reinforced epoxy
TF	–	Teflon sheet

Third Field: Coating Description

AC	–	Acrylic nitrocellulose paint
AD	–	Knitted aluminum wire mesh
AF	–	Aluminum foil
AG	–	Aluminized glass, 1500 conductive filaments per inch per ply
AH	–	Aluminized glass, 3100 conductive filaments per inch per ply
AI	–	Aluminized glass, 4480 conductive filaments per inch per ply
AJ	–	Aluminized glass, 8960 conductive filaments per inch per ply
AL	–	Sandwich of style 104 glass scrim cloth between perforated aluminum foil
AR	–	Woven aluminum wire fabric
AW	–	Aluminum metal fibers
CR	–	Woven copper wire fabric
CW	–	Unidirectional copper wires
CZ	–	Woven bronze wire fabric
IP	–	Intumescent paint
NY	–	Epoxy-resin-impregnated nylon fabric
SE	–	Silver pigmented epoxy paint
SG	–	Silver-filled, epoxy-resin-impregnated, style 181 glass fabric
C	–	100% surface coverage by coating
J	–	13-by-24 mesh of double-stranded wire
N	–	Bidirectional filament orientation
P	–	Metal strip along panel edge
O	–	Unidirectional filament orientation
U	–	100-by-100 mesh
W	–	60-by-60 mesh
X	–	120-by-120 mesh
Z	–	200-by-200 mesh

Fourth Field: Undercoating Description

AI	–	Aluminized glass
AR	–	Woven aluminum wire fabric
KF	–	Kapton film
PU	–	Polyurethane paint
ALCO	–	Aluminum honeycomb core

Fifth Field (optional): Environmental Exposure

BW	–	Boiling water
JP	–	Immersion in jet fuel
RH	–	100% relative humidity at 140°F
SD	–	Immersion in hydraulic fluid
SS	–	3% salt spray
WM	–	Weather-O-Meter

Table A-2. General Description of Test Panels

Test serial number	Test panel	Coating	Test discharge	Remarks
292 GP12 AD08J 0000	Graphite	Aluminum wire mesh	95 kA	Coating damage (4 in. tear in wire mesh and delamination from substrate)
293 GP13 AD08J 0000 BW	Graphite	Aluminum wire mesh	78 kA	Panel boiled in water 70 hr; discharge penetrated coating and caused limited delamination and damage to substrate
294 FG56 AD08J 0000 BW	Fiberglass	Aluminum wire mesh	75 kA	Panel boiled in water 70 hr; discharge partially destroyed coating between arc attachment point and electrical ground; no damage to substrate
295 FG57 AD08J 0000	Fiberglass	Aluminum wire mesh	81 kA	Discharge partially destroyed coating between arc attachment point and electrical ground; no damage to substrate
296 GP14 AR08X 0000	Graphite	Aluminum wire fabric	129 kA	1 sq in. of fabric removed at arc attachment point; no damage to substrate
297 GP15 AR08X 0000 BW	Graphite	Aluminum wire fabric	124 kA	Panel boiled in water 70 hr; discharge caused wire vaporization at arc attachment point; no damage to substrate
298 FG58 NY04C AR08	Fiberglass	Aluminum wire fabric	105 kA	Discharge produced a [illegible] in. dia hole in fabric coating; no damage to substrate
299 FG59 NY04C AR08 BW	Fiberglass	Aluminum wire fabric	99 kA	Panel boiled in water 70 hr; discharge removed wire fabric from ¼ sq in. area; no damage to substrate
300 GP16 AR08X FG04	Graphite	Aluminum wire fabric	205 kA	Discharge damaged 1[illegible] in. dia area of coating; no damage to substrate
301 GP17 AR08X FG04	Graphite	Aluminum wire fabric	224 C	A 66 kA discharge triggered a 224 C discharge at a 210 A dc current for 1.07 sec; it destroyed a 1 1/8 in. dia area of coating and burned a 1 in. dia crater in substrate
302 GP18 00000 0000	Graphite	Uncoated	95 kA	Discharge delaminated about 6 sq in. of panel face and produced a ¼ in. crack on the backside
303 GP19 00000 0000 BW	Graphite	Uncoated	93 kA	Panel boiled in water 70 hr; discharge delaminated about 6 sq in. of the panel face and produced a ¼ sq in. hole through panel
304 BR23 AR08X 0000	Boron	Aluminum wire fabric	103 kA	Coating removed at discharge point; no other damage visible
305 BR24 AR08X 0000	Boron	Aluminum wire fabric	34 C	A 100 kA discharge triggered a 34 C discharge at a 75 A dc current for 0.2 sec; minor damage to coating; no damage to substrate
306 BR25 AD08J 0000	Boron	Aluminum wire mesh	85 kA	Wire coating destroyed between arc attachment point and electrical ground; no damage to substrate
307 BR26 AD08J 0000 BW	Boron	Aluminum wire mesh	75 kA	Panel boiled in water 70 hr; wire coating damaged between arc attachment point and electrical ground; substrate sustained a 2 in. crack
308 BR27 SE12C 0000	Boron	Silver paint	120 kA	Moderate damage to coating; no damage to substrate
309 BR28 SE06C 0000	Boron	Silver paint	99 kA	Considerable damage to coating; no damage to substrate
310 FG60 SE08C 0000	Fiberglass	Silver paint	77 kA	Discharge severely damaged coating; no damage to substrate
311 FG61 SE08C 0000	Fiberglass	Silver paint	78 kA	Discharge severely damaged coating; no damage to substrate
312 BR29 00000 0000	Boron	Uncoated	75 kA	Discharge caused a ¼ in. hole through panel, and seriously weakened panel
313 BR30 00000 0000 [illegible]	Boron	Uncoated	42 kA	Panel exposed to 100% RH at 140°F for 30 days; discharge produced a ½ in. dia hole through panel
314 BR[illegible] AR08X 0000	Boron	Aluminum wire fabric	109 kA	Panel tested with two discharges: the first, with a peak current of 109 kA, produced no damage to coating or substrate; the second, directed to the same spot, with a peak current of 105 kA, removed some coating at arc attachment point, but produced no damage to substrate

Table A 2 Continued

Test serial number	Test panel	Coating	Test discharge	Remarks
315 BR32 AR08X 0000 RH	Boron	Aluminum wire fabric	94 kA	Panel exposed to a 100% RH at 140°F for 30 days, some coating removed at arc attachment point no damage to substrate
316 BR33 AR08X 0000 SS	Boron	Aluminum wire fabric	109 kA	Panel exposed to 3% salt spray 90 days minor coating damage no damage to substrate
317 BR34 AR08X 0000 SS	Boron	Aluminum wire fabric	111 kA	Panel exposed to 3% salt spray 61 days minor coating damage no damage to substrate
318 BR35 AR08X 0000 SS	Boron	Aluminum wire fabric	109 kA	Panel exposed to 3% salt spray 30 days, slight removal of coating at arc attachment point no damage to substrate
319 BR36 AR08X 0000 SD	Boron	Aluminum wire fabric	108 kA	Panel immersed in hydraulic fluid 30 days slight removal of coating at arc attachment point no damage to substrate
320 BR37 AR08X 0000 JP	Boron	Aluminum wire fabric	104 kA	Panel soaked in JP 4 jet fuel 30 days, minor removal of coating at arc attachment point, no damage to substrate
321 BR38 AR08X 0000 WM	Boron	Aluminum wire fabric	105 kA	Panel exposed in Weather O Meter 30 days slight removal of coating at arc attachment point no damage to substrate
322 BR39 AR08X 0000	Boron	Aluminum wire fabric	203 kA	Coating slightly damaged in 1¼ in dia area no damage to substrate
323 BR40 AR08X 0000	Boron	Aluminum wire fabric	140 C	A 96 kA discharge triggered a 140 C discharge at a 136 A dc current for 1 03 sec, it produced small pit marks on coating in 3 by 4 in area, slight damage of substrate at some pit locations
324 BR41 SE08C KF01	Boron	Silver paint	98 kA	Moderate damage to coating no damage to substrate
325 BR42 AC03P KF01	Boron	Acrylic paint	151 kA	Discharge vaporized 8 in of aluminum strips on each side of panel mechanical forces at discharge probe caused two ¼ in cracks in boron panel at arc attachment point, no electrical damage to substrate
326 FG62 AD08J 0000 RH	Fiberglass	Aluminum wire mesh	87 kA	Panel exposed in 100% RH at 140°F for 30 days, coating wires destroyed between arc attachment point and electrical ground, no damage to substrate
327 FG63 AD08J 0000 SS	Fiberglass	Aluminum wire mesh	82 kA	Panel exposed to 3% salt spray for 30 days, wires across face of panel between arc attachment point and electrical ground partially destroyed, no damage to substrate
328 FG64 AD08J 0000 WM	Fiberglass	Aluminum wire mesh	82 kA	Panel exposed in Weather O Meter for 30 days, wires between arc attachment point and electrical ground partially destroyed no damage to substrate
329 FG65 AD08J 0000 SD	Fiberglass	Aluminum wire mesh	72 kA	Panel immersed in hydraulic fluid for 30 days, discharge partially destroyed wires between arc attachment point and electrical ground, no damage to substrate
330 FG66 SG08C 0000	Fiberglass	Silver impregnated fabric	75 kA	About 3 sq in of coating removed at arc attachment point, coating also burned and partially separated from panel face no damage to substrate
331 FG67 SG08C 0000 RH	Fiberglass	Silver impregnated fabric	94 kA	Panel exposed to 100% RH at 140°F for 30 days, coating delaminated from panel, no damage to substrate
332 FG68 SG08C 0000 SS	Fiberglass	Silver impregnated fabric	85 kA	Panel exposed to a 3% salt spray for 30 days discharge delaminated coating from panel face no damage to substrate
333 FG69 SG08C 0000 SD	Fiberglass	Silver impregnated fabric	67 kA	Panel immersed in hydraulic fluid for 30 days discharge removed most of coating from panel face no damage to substrate
334 FG70 SG08C 0000 JP	Fiberglass	Silver impregnated fabric	83 kA	Panel soaked in JP 4 jet fuel 30 days, discharge delaminated coating along panel edges, no damage to substrate
335 FG71 SG08C 0000 WM	Fiberglass	Silver impregnated fabric	71 kA	Panel exposed in Weather O Meter 30 days discharge removed all coating from panel face between arc attachment point and ground no damage to substrate

Table A 2 - Continued

Test serial number	Test panel	Coating	Test discharge	Remarks
336 BR43 CR09U 0000 BW	Boron	Copper wire fabric	106 kA	Panel boiled in water 70 hr, discharge caused slight melting of coating at arc attachment point, no damage to substrate
337 BR44 CR09U 0000	Boron	Copper wire fabric	111 kA	Coating slightly damaged at arc attachment point, no damage to substrate
338 BR45 AR16W 0000 BW	Boron	Aluminum wire fabric	109 kA	Panel boiled in water 70 hr, no damage to substrate or wire fabric
339 BR46 AR16W 0000	Boron	Aluminum wire fabric	111 kA	Discharge caused slight damage to coating at arc attachment point, no damage to substrate
340 BR47 AL03C 0000	Boron	Aluminum foils	105 kA	Discharge removed 1 sq in. of outer aluminum foil, no damage to inner foil or substrate
341 BR48 AL03C 0000/BW	Boron	Aluminum foils	106 kA	Panel boiled in water 70 hr, discharge removed about 1 sq in. of outer aluminum foil, no damage to inner foil or substrate
342 BR49 AF01C 0000	Boron	Aluminum foil	105 kA	Discharge removed about 3 sq in. of aluminum foil at arc attachment point, no damage to substrate
343 BR50 AF01C 0000 BW	Boron	Aluminum foil	103 kA	Discharge removed about 3 sq in. of aluminum foil at arc attachment point, no damage to substrate
344 BR38 AC03P KF01	Boron	Acrylic paint	154 kA	8- by 8-in. panel with copper tape along each edge parallel to induced current flow, discharge destroyed by 4- by 4-in. section
345 GP20 00000 0000/RH	Graphite	Uncoated	83 kA	Panel exposed to 100% RH at 140°F for 30 days, discharge severely damaged an area of about 6 sq in. on panel face, damage visible on area of about ¼ sq in. on panel backside
346 GP21 00000 0000	Graphite	Uncoated	87 kA	Discharge severely damaged an area of about 6 sq in. on panel face, ¼ in. crack was visible on backside
347 GP22 SE12C 0000	Graphite	Silver paint	184 kA	Discharge removed an 8-sq in. area of coating, substrate resin destroyed in a 1½-in.-dia area, delaminating outer plies in this zone
348 GP23 AR08X 0000	Graphite	Aluminum wire fabric	108 C	A 100 kA discharge triggered a 108 C discharge at a 240 A dc current for 0.45 sec, an area of coating 2¼ by 1 in. was vaporized, a ¼-in.-dia crater was burned into substrate
349 GP24 AR08X 0000/SS	Graphite	Aluminum wire fabric	103 kA	Panel exposed to 3% salt spray 30 days, no damage by discharge to panel or coating
350 GP25 AR08X 0000	Graphite	Aluminum wire fabric	185 C	A 100 kA discharge triggered a 185 C discharge at a 220 A dc current for 0.84 sec, a 1¼-in.-dia area of wire fabric was vaporized, severe damage to substrate
351 GP26 AR08X 0000/SD	Graphite	Aluminum wire fabric	112 kA	Panel immersed in hydraulic fluid 30 days, no damage by discharge to coating or panel
352 GP27 AR08X 0000/JP	Graphite	Aluminum wire fabric	104 kA	Panel soaked in JP 4 jet fuel 30 days, discharge removed some coating at contact point, no damage to wire fabric or substrate
353 GP28 AR08X 0000/WM	Graphite	Aluminum wire fabric	104 kA	Panel exposed in Weather O Meter 30 days, discharge caused slight damage to wire fabric at arc attachment point, no damage to substrate
354 GP29 AR08X 0000/SS	Graphite	Aluminum wire fabric	107 kA	Panel exposed to 3% salt spray 61 days, a ¼-in. square of wire fabric was delaminated from substrate and substrate slightly damaged at arc attachment point
355 GP30 AR08X 0000/SS	Graphite	Aluminum wire fabric	105 kA	Panel exposed to 3% salt spray 90 days, no damage to substrate
356 BR51 00000 0000	Boron	Uncoated	49 kA	Entire panel badly damaged by discharge
357 BR52 00000 0000	Boron	Uncoated	104 kA	Entire panel badly damaged by discharge
358 BR53 AJ09N 0000/SS	Boron	Aluminized glass	102 kA	Layers oriented 0° and 90°, panel exposed to 3% salt spray 30 days, coating damaged in 5/8-in.-dia area, no damage to substrate
359 BR54 AI09N 0000/SS	Boron	Aluminized glass	209 kA	Layers oriented -45° and +45°, panel exposed to 3% salt spray 30 days, outer layer of coating badly delaminated from 1¼-in.-dia discharge area, no damage to substrate

Table A-2—Continued

Test serial number	Test panel	Coating	Test discharge	Remarks
360 BR55 AC03C AF06	Boron	Aluminum foil	105 C	A 97 kA discharge triggered a 105 C discharge at a 195 A dc current for 0.54 sec, coating melted in 2¼ by 1¼ in. area, substrate badly damaged in 1 by ¾ in. area
361 BR56 AC03C AF06	Boron	Aluminum foil	209 kA	Coating vaporized in ¼ by 3/8 in. area, no damage to substrate[a]
362 BR57 SE12C KF01	Boron	Silver paint	95 kA	Discharge darkened coating and damaged substrate
363 BR58 SE12C PU02	Boron	Silver paint	93 kA	Discharge removed coating from six 3/16 in.-dia areas and made two 1/8 in. holes through substrate
364 GP31 SE06C KF01	Graphite	Silver paint	109 kA	Coating damaged at arc attachment point and electrical ground, no damage to substrate
365 GP32 AC03P KF01	Graphite	Acrylic paint	93 kA	Substrate punctured and damaged
366 GP33 00000 0000	Graphite	Uncoated	98 kA	About 4 sq in. of panel badly scorched and delaminated, but panel was not punctured
367 GP34 00000 0000	Graphite	Uncoated	187 kA	About 6 sq in. of panel badly scorched and delaminated, but panel was not punctured
368 GP35 AJ09N 0000/SS	Graphite	Aluminized glass	104 kA	Layers oriented 0° and 90°, panel exposed to 3% salt spray 30 days, coating damaged in ¾ in.-dia discharge area, no damage to substrate; some corrosion of coating
369 GP36 AI09N 0000/SS	Graphite	Aluminized glass	206 kA	Layers oriented -45° and +45°, panel exposed to 3% salt spray 30 days, outer coating layer delaminated in 1½-in.-dia. discharge area, no damage to substrate, coating corrosion
370 GP37 IP04C AI14	Graphite	Aluminized glass	105 C	Layers oriented 0°, 90°, 90°, and 0°, a 95 kA discharge triggered a 105 C discharge at a 187-A dc current for 0.56 sec, coating was vaporized in ¾-in.-dia area; a ¾-in.-dia crater was burned in substrate
371 GP38 AC03C AF06	Graphite	Aluminum foil	203 kA	Coating melted in 7/16 by 5/16 in. area, no damage to substrate
372 BR59 SE04 KF01	Boron	Silver paint	98 kA	Discharge damaged substrate
373 BR60 AI05C 0000	Boron	Aluminized glass	105 C	Layers oriented -45° and +45°, a 91-kA discharge triggered a 105-C discharge at a 180-A dc current for 0.585 sec; discharge made a 1/8- by 3/16-in. hole through coating into substrate, slightly damaging substrate; arc wandered over large area of panel causing only slight damage to coating
374 GP39 AC03C AF06	Graphite	Aluminum foil	109 C	A 98-kA discharge triggered a 109 C discharge at a 195 A dc current for 0.56 sec, coating was melted in 1 in.-dia area, a 1-in.-dia crater was burned in substrate
375 GP40 SE12C PU02	Graphite	Silver paint	88 kA	Discharge removed coating and outer plies of substrate in three areas, ½ by 2, 3/8 by 1¾, and ¼ by 1 in.; substrate severely damaged
376 BR61 SE04C KF01	Boron	Silver paint	100 kA	Discharge severely damaged panel and made a 1/16- by ¼-in. hole through substrate
377 BR62 AI05C 0000	Boron	Aluminized glass	200 C	Layers oriented -45° and +45°, a 93-kA discharge triggered a 200-C discharge at a 192-A dc current for 1.04 sec, discharge badly damaged panel in a 2- by 1-in. area and made a 1 in.-dia hole through substrate
378 GP41 SE04C PU02	Graphite	Silver paint	89 kA	Discharge severely damaged coating and substrate
379 GP42 SE04C 0000	Graphite	Silver paint	88 kA	Discharge removed coating from 1¾ in.-dia area, substrate damaged in ¾-in.-dia area
380 GP43 AF01C 0000/SS	Graphite	Aluminum foil	81 kA	Panel exposed to 3% salt spray 30 days, which caused severe corrosion of coating; discharge removed remainder of coating and broke substrate into three pieces
381 GP44 AF01C 0000	Graphite	Aluminum foil	111 kA	Discharge removed about 3 sq in. of aluminum foil, no damage to substrate
382 BR63 SE06C 0000	Boron	Silver paint	62 kA	Discharge damaged coating and made a 3/16 by ⅛ in. hole through substrate

Table A-2--Continued

Test serial number	Test panel	Coating	Test discharge	Remarks
383 BR64 SE12C 0000	Boron	Silver paint	89 kA	Discharge damaged coating and made a ¼ in. dia hole through substrate
384 GP45 SE12C 0000	Graphite	Silver paint	116 kA	No damage to coating, substrate severely weakened
385 GP46 SE06C 0000	Graphite	Silver paint	105 kA	Coating and substrate severely damaged
386 GP47 AI18N 0000	Graphite	Aluminized glass	209 kA	Eight layers oriented 0° and 90° ¼ in. dia area of coating damaged, no damage to substrate
387 GP48 AR08X 0000	Graphite	Aluminum wire fabric	196 C	A 83 kA discharge triggered a 196 C discharge with a 189 A dc current for 1.04 sec coating destroyed in 1 1/16 in. dia area, a 1 in. dia crater burned in substrate
388 GP49 AR04Z FG04	Graphite	Aluminum wire fabric	200 kA	Coating damaged in 1¼ in. dia cloverleaf pattern, first ply of substrate sustained damage in 1/8 in. dia area
389 GP50 AR04Z FG04	Graphite	Aluminum wire fabric	176 C	A 91 kA discharge triggered a 176 C discharge at a 169 A dc current for 1.04 sec, about 1 sq in. of coating severely burned by discharge, the high current arc wandered over a 5- by 6-in. area of panel causing moderate damage to coating, no damage to substrate
390 TF01 00000 0000	Teflon sheet	None	-	Panel used for triboelectric charging studies only
391 BR65 CW07Q 0000	Boron	6.3-mil, Formvar coated, copper wires	43 kA	Wire layer oriented 90° with 126 wires per inch, discharge severely damaged about 1 sq in. of both coating and substrate at arc attachment point
392 BR66 CW07Q 0000	Boron	6.3-mil, Formvar coated, copper wires	102 kA	Wire layer oriented parallel to induced current path with 126 wires per inch, discharge damaged about ¼ sq in. of both coating and substrate at arc attachment point, a ½ in. strip of copper wire coating was vaporized from arc attachment point to ground
393 BR67 CW06N 0000	Boron	2.5-mil, Formvar coated, copper wires	115 kA	Wire layers oriented 0° and 90° with 350 wires per inch, discharge caused random damage to coating, substrate slightly damaged at arc attachment point
394 BR68 CW06N 0000	Boron	2.5-mil, Formvar coated, copper wires	106 kA	Wires oriented 90° and 0° with 350 wires per inch, discharge damaged most of wire in a 1 in. strip from arc attachment point to electrical ground, substrate damage over ¼ sq in. area
395 BR69 CW05Q 0000	Boron	5-mil uncoated copper wires	119 kA	Wires oriented parallel to induced current path with 80 wires per inch, wires slightly damaged at arc attachment point, no damage to substrate
396 BR70 CW05Q 0000	Boron	5-mil uncoated copper wires	120 kA	Wires oriented parallel to induced current path with 160 wires per inch, 3 or 4 wires broken at arc attachment point, no damage to substrate
397 BR71 CW02Q 0000	Boron	1.4-mil, Formvar coated, copper wire	101 kA	Wires oriented parallel to induced current path with 530 wires per inch, a 1½ in. wide strip of coating badly damaged between arc attachment point and electrical ground
398 BR72 CW04Q 0000	Boron	1.4-mil, Formvar coated, copper wire	106 kA	Two layers of wire oriented parallel to induced current path with 530 wires per inch in each layer, a 1-in. wide strip of copper wire coating was removed between arc attachment point and electrical ground
399 BR73 CW04N 0000	Boron	1.4-mil, Formvar coated, copper wire	98 kA	Wires oriented 0° and 90° with 530 wires per inch, moderate damage to coating at arc attachment point, no damage to substrate
400 BR74 AG08N 0000	Boron	Aluminized glass	70 kA	Layers oriented 90° and 0°, both layers of aluminized glass filaments damaged, small hole in substrate
401 BR75 AH04Q 0000	Boron	Aluminized glass	73 kA	Layer oriented 90°, discharge badly damaged panel making 2 in. crack and six holes, moderate coating damage shows that panel carried most of current

Table A-2 Continued

Test serial number	Test panel	Coating	Test discharge	Remarks
402 BR76 AG04Q 0000	Boron	Aluminized glass	56 kA	Layer oriented parallel to induced current path, discharge removed most of coating and badly damaged substrate
403 BR77 AH08N 0000	Boron	Aluminized glass	109 kA	Layers oriented 0° and 90°, discharge removed about 1 sq in. of outer (0°) ply at arc attachment point, no damage to underlayer or substrate
404 BR78 AH04Q 0000	Boron	Aluminized glass	78 kA	Layer oriented parallel to induced current path, discharge caused severe damage to coating and substrate
405 CP51 AG04Q 0000	Graphite	Aluminized glass	105 kA	Layer oriented parallel to induced current path, discharge removed about 1 sq in. of coating at arc attachment point, no damage to substrate
406 GP52 AH04Q 0000	Graphite	Aluminized glass	78 kA	Layer oriented parallel to induced current path, discharge removed about 6 sq in. of coating, substrate showed 1½ and ¾ in. cracks
407 BR79 CW05Q 0000	Boron	5 mil uncoated copper wires	56 kA	Wire layer oriented 90° with 160 wires per inch, both coating and substrate severely damaged
408 BR80 CW05Q 0000	Boron	5 mil uncoated copper wires	75 kA	Wire layer oriented 90° with 80 wires per inch, both coating and panel severely damaged
409 BR81 CW03Q 0000	Boron	2.5 mil, Formvar coated, copper wires	59 kA	Wire layer oriented 90° with 350 wires per inch, both coating and substrate severely damaged
410 BR82 CW02Q 0000	Boron	1.4 mil, Formvar coated copper wires	52 kA	Wire layer oriented 90° with 530 wires per inch, discharge caused excessive damage to both coating and panel
411 GP53 AH11N 0000	Graphite	Aluminized glass	108 kA	Layers oriented 0°, 90°, and 0°, discharge removed about 1 sq in. of outer layer and slightly damaged middle layer, no damage to inner layer or substrate
412 GP54 AH11Q 0000	Graphite	Aluminized glass	108 kA	Three layers oriented parallel to induced current path, slight damage was caused to outer layers, no damage to substrate
413 GP55 AH15N 0000	Graphite	Aluminized glass	108 kA	Layers were oriented 0°, 90°, 90°, and 0°, discharge removed about 1 sq in. of outer layer and ½ sq in. of next layer, no damage to inner layers or substrate
414 GP56 AH07N 0000	Graphite	Aluminized glass	108 kA	Layers oriented 0° and 90°, discharge removed ½ sq in. of outer layer, inner layer slightly damaged, no damage to substrate
415 BR83 AG12N 0000	Boron	Aluminized glass	98 kA	Layers oriented 0°, 90°, 90° and 0° discharge removed about 4 sq in. of outer layer, coating delaminated over 5 by 6 in. area, no damage to substrate
416 BR84 AH11Q 0000	Boron	Aluminized glass	108 kA	Layers oriented 0°, 90°, and 0° discharge caused very little damage to coating, no damage to substrate
417 BR85 AH11N 0000	Boron	Aluminized glass	109 kA	Layers oriented 0°, 90°, and 0°, discharge removed about 1 sq in. of outer layer, next layer slightly damaged, no damage to substrate
418 BR86 AC03C 0000	Boron	Acrylic paint	85 kA	8 by 8 in. panel with copper tape along each edge parallel to induced current flow, discharge severely weakened 3½ in. dia panel area, copper diverter strips appeared to carry some current
419 BR87 AR04Z 0000	Boron	Aluminum wire fabric	79 C	A 100 kA discharge triggered a 79 C discharge at a 180 A dc current for 0.44 sec, a ½ in. dia area of wire fabric destroyed at arc attachment point, no damage to substrate
420 BR88 AR04Z 0000	Boron	Aluminum wire fabric	288 C	A 100 kA discharge triggered a 288 C discharge at a 200 A dc current for 1.44 sec, coating and substrate badly damaged, a 1 in. dia hole burned through panel, boron filaments between hole and electrical ground badly damaged

Table A-2—Continued

Test serial number	Test panel	Coating	Test discharge	Remarks
421 BR89 AR04Z 0000	Boron	Aluminum wire fabric	138 C	A 100 kA discharge triggered a 138 C discharge at a 150 A dc current for 0.92 sec, a 3 by 4 in. area of both coating and substrate badly damaged, ⅜ in. dia hole burned through panel
422 BR90 AR04Z 0000	Boron	Aluminum wire fabric	186 kA	Panel severely damaged by mechanical forces produced by the discharge due to inadequate panel mounting procedure
423 GP57 AR04Z 0000	Graphite	Aluminum wire fabric	186 kA	Panel severely damaged by mechanical forces produced by discharge due to inadequate panel mounting procedure
424 GP58 AR04Z 0000	Graphite	Aluminum wire fabric	213 C	A 100 kA discharge triggered a 213 C discharge at a 245 A dc current for 0.87 sec, wire fabric coating vaporized in 1¼ in. dia area, 1 1/3 in. dia crater burned into substrate
425 GP59 IP04C AR04	Graphite	Aluminum wire fabric	98 C	A 94 kA discharge triggered a 98 C discharge with a 189 A dc current for 0.52 sec, coating destroyed in 1¼ by 7/8 in. area, 1¼ by 7/8 in. crater burned in substrate
426 GP60 AR04Z 0000	Graphite	Aluminum wire fabric	209 kA	Coating damaged in 1½ by 1¼ in. area and destroyed in ½ by ¼ in. area, no damage to substrate
427 BR91 AR04Z 0000	Boron	Aluminum wire fabric	112 kA	Panel subjected to two discharges, the first had a peak current of 112 kA, the second 111 kA, no damage to substrate
428 BR92 AR04Z 0000	Boron	Aluminum wire fabric	112 kA	No damage to substrate
429 GP61 AJ05O 0000	Graphite	Aluminized glass	105 kA	Layer oriented parallel to induced current path, coating damaged over ½ by 1⅜ in. area, no damage to substrate
430 GP62 AI05N 0000	Graphite	Aluminized glass	108 kA	Layers oriented 0° and 90°, coating damaged over ½ in. dia area, no damage to substrate
431 GP63 AJ09N 0000	Graphite	Aluminized glass	111 kA	Layers oriented 90° and 0°, discharge caused slight damage to coating at arc attachment point, no damage to substrate
432 GP64 AJ09N 0000	Graphite	Aluminized glass	110 kA	Layers oriented 0° and 90°, no damage to substrate, but coating slightly marred
433 GP65 AJ09N 0000	Graphite	Aluminized glass	110 kA	Layers oriented +45° and -45°, no damage to substrate, but coating slightly marred
434 GP66 AI05O 0000	Graphite	Aluminized glass	110 kA	Two layers parallel to induced current path, coating damaged over ¼ by 1½ in. area, slight damage to substrate at arc attachment point
435 BR93 AJ02O 0000	Boron	Aluminized glass	98 kA	Layer oriented along the induced current path, coating damaged over 2½ by 7 in. area, no damage to substrate
436 BR94 AI05N 0000	Boron	Aluminized glass	109 kA	Layers oriented 0° and 90°, discharge damaged coating in 1 in. dia area, no damage to substrate
437 BR95 AJ09N 0000	Boron	Aluminized glass	112 kA	Layers oriented 90° and 0°, coating damaged in ½ in. dia area, no damage to substrate
438 BR96 AI09N 0000	Boron	Aluminized glass	112 kA	Layers oriented 0° and 90°, coating damaged in ½ in. dia area, no damage to substrate
439 BR97 AJ09N 0000	Boron	Aluminized glass	112 kA	Layers oriented -45° and +45°, coating damaged in ½ in. dia area; no damage to substrate
440 BR98 AI05O 0000	Boron	Aluminized glass	100 kA	Two layers parallel to induced current path, coating damaged in an area 2 by 7 in.; no damage to substrate
441 GP67 AR08X 0000	Graphite	Aluminum wire fabric	89 C	A 110 kA discharge triggered an 89 C discharge at a 78 A dc current for 1.14 sec; wire fabric coating vaporized in ¾ in. dia area and crater-shaped hole burned in substrate

Table A-2—Continued

Test serial number	Test panel	Coating	Test discharge	Remarks
442-GP68-AR08X-0000	Graphite	Aluminum wire fabric	101 C	A 110-kA discharge triggered a 101-C discharge at a 23-A dc current for 4.35 sec, wire fabric coating vaporized over 1½-in.-dia area; 1-in.-dia crater burned into substrate
443-GP69-AR08X-0000	Graphite	Aluminum wire fabric	98 C	A 110-A discharge triggered a 98-C discharge at a 390-A dc current for 0.25 sec, wire fabric coating vaporized over 1-in.-dia area; 1-in.-dia crater burned into substrate
444-GP70-AC03C-AR08	Graphite	Aluminum wire fabric	199 kA	Wire fabric coating severely damaged in an area 2 by 1¼ in., substrate damaged in ½-in.-dia area
445-GP71-AR08X-0000	Graphite	Aluminum wire fabric	186 kA	Wire fabric coating severely damaged in area 2½ by 3 in.; substrate damaged in ¾-in.-dia area
446-GP72-AR04Z-0000	Graphite	Aluminum wire fabric	206 C	A 90-kA discharge triggered a 206-C discharge at a 184-A dc current for 1.12 sec, wire fabric coating vaporized over 1-1/8-in.-dia area, 1-in.-dia crater burned into substrate
447-BR99-AR04Z-0000	Boron	Aluminum wire fabric	29 C	A 90-kA discharge triggered a 29-C discharge at a 120-A dc current for 0.24 sec, no damage to coating or substrate
448-BR00-AR08X-0000	Boron	Aluminum wire fabric	86 C	A 110-kA discharge triggered an 86-C discharge at a 75-A dc current for 1.14 sec, wire fabric coating severely damaged over area 1 by 2 in.; 3/8-in.-dia hole burned through substrate
449-BR01-AR08X-0000	Boron	Aluminum wire fabric	2.4 C	A 110-kA discharge triggered a 2.4-C discharge at a 24-A dc current for 0.1 sec; no damage to substrate
450-BR02-AR08X-0000	Boron	Aluminum wire fabric	85 C	A 110-kA discharge triggered an 85-C discharge at a 352-A dc current for 0.24 sec; some wire coating vaporized in random fashion over area 2 by 3 in., no damage to substrate
451-BR03-AC03C-AR08	Boron	Aluminum wire fabric	196 kA	Small crack in substrate caused by mechanical collision of discharge probe with substrate, no electrical damage
452-BR04-AR08X-0000	Boron	Aluminum wire fabric	191 kA	Panel severely damaged by mechanical forces produced by discharge due to improper panel mounting procedure
453-BR05-AC03C-AR08	Boron	Aluminum wire fabric	186 kA	Discharge removed 40% of acrylic paint between arc attachment point and ground, some wire fabric coating vaporized at arc attachment point, no damage to substrate except for small crack caused by collision of probe with substrate
454-BR06-AC03C-AR04	Boron	Aluminum wire fabric	110 kA	Discharge removed a 1- by 1-in. square of acrylic paint, no damage to coating or substrate
455-BR07-AC03C-AR04	Boron	Aluminum wire fabric	50 C	A 110-kA discharge triggered a 50-C discharge at a 49-A dc current for 1.03 sec; wire fabric coating and substrate severely damaged in ½- by 4-in. area, 3/8-in. hole burned through substrate
456-BR08-AC03C-AR04	Boron	Aluminum wire fabric	92 C	A 90-kA discharge triggered a 92-C discharge at a 90-A dc current for 1.02 sec; wire fabric coating and substrate severely damaged in area ¾ by 3 in.; 3/8- by 5/8-in. hole burned through substrate
457-BR09-AC03C-AR04	Boron	Aluminum wire fabric	140 C	A 90-kA discharge triggered a 140-C discharge at a 135-A dc current for 1.04 sec, acrylic paint and metal removed from coating in random pattern; no damage to substrate
458-GP73-AC03C-AR04	Graphite	Aluminum wire fabric	196 kA	Wire fabric coating vaporized in 1-in.-dia area, substrate moderately damaged in ¾-in.-dia area

Table A-2—Continued

Test serial number	Test panel	Coating	Test discharge	Remarks
459 GP74 AC03C AR04	Graphite	Aluminum wire fabric	186 C	A 90-kA discharge triggered a 186-C discharge at a 184-A dc current for 1.01 sec, wire fabric coating vaporized from 1-1/8-in.-dia area, 1-in. dia crater burned in substrate
460 GP75 AC03C AR04	Graphite	Aluminum wire fabric	–	Characteristics of discharge uncertain due to instrumentation failure, wire fabric coating vaporized from area 3/8 by 5/8 in., substrate damaged at arc attachment point
461 GP76 AC03C AR04	Graphite	Aluminum wire fabric	56 C	A 110-kA discharge triggered a 56-C discharge at a 54-A dc current for 1.04 sec, some wire fabric coating vaporized and 1- by 5/8-in. crater burned into substrate
462 GP77 AC03C AR04	Graphite	Aluminum wire fabric	100 C	A 90-kA discharge triggered a 100-C discharge at a 100-A dc current for 1 sec, some wire fabric coating vaporized and 5/8-in.-dia crater burned into substrate
463 BR10 AC03C A114	Boron	Aluminized glass	128 kA	Layers oriented 0°, 90°, 90°, and 0°, discharge damaged 1-in.-dia area of coating and substrate
464 BR11 AC03C A114	Boron	Aluminized glass	196 kA	Layers oriented 0°, 90°, 90°, 0°, discharge removed most of coating between arc attachment point and ground, boron panel seriously weakened
465 BR12 AC03C A114	Boron	Aluminized glass	2.3 C	Layers oriented 0°, 90°, 90°, and 0°, a 110-kA discharge triggered a 2.3-C discharge at a 39-A dc current for 0.06 sec, coating damaged over area 1 by 1½ in., no damage to substrate
466 BR13 AC03C A114	Boron	Aluminized glass	97 C	Layers oriented 0°, 90°, 90°, and 0°, a 90-kA discharge triggered a 97-C discharge at a 90-A dc current for 1.08 sec, coating and substrate damaged over area 2¼ by 3 in. and a ½-in.-dia hole burned through substrate
467 GP78 AC03C A114	Graphite	Aluminized glass	119 kA	Layers oriented 0°, 90°, 90°, and 0°, coating removed from ¾-in.-dia area, no damage to substrate
468 GP79 AC03C A114	Graphite	Aluminized glass	175 kA	Layers oriented 0°, 90°, 90°, and 0°, discharge damaged coating over 1-in.-dia area, small crack in substrate at arc attachment point caused by collision of probe with substrate
469 GP80 AC03C A114	Graphite	Aluminized glass	55 C	Layers oriented 0°, 90°, 90°, and 0°, a 110-kA discharge triggered a 55-C discharge at a 53-A dc current for 1.04 sec, coating vaporized in 1-in.-dia area, 3/16-in.-dia hole burned through panel
470 GP81 AC03C A114	Graphite	Aluminized glass	106 C	Layers oriented 0°, 90°, 90°, and 0°, a 90-kA discharge triggered a 106-C discharge at a 96-A dc current for 1.1 sec, coating vaporized from 1-in.-dia area, ¾-in.-dia crater burned into substrate
471 GP82 AC03C A114	Graphite	Aluminized glass	199 C	Layers oriented 0°, 90°, 90°, and 0°, a 90-kA discharge triggered a 199-C discharge at a 184-A dc current for 1.085 sec, coating removed from 1 1/8-in.-dia area, 1-in.-dia crater burned into substrate
472 BR14 AF08C 0000	Boron	Aluminum foil	194 kA	Discharge vaporized 3/8-in.-dia area of coating, no damage to substrate
473 GP83 AF08C 0000	Graphite	Aluminum foil	192 kA	Discharge vaporized ¼-in.-dia area of coating, no damage to substrate
474 BR15 AF08C 0000	Boron	Aluminum foil	203 C	A 97-kA discharge triggered a 203-C discharge at a 195-A dc current for 1.04 sec, coating melted in 2-in.-dia area, substrate severely damaged in same area, 3/8- by ½-in. hole burned through panel
475 GP84 AF08C 0000	Graphite	Aluminum foil	216 C	A 96-kA discharge triggered a 216-C discharge at a 202-A dc current for 1.07 sec, coating melted from 1 3/8-in.-dia area, 1 1/8-in.-dia crater burned in substrate
476 GP85 A110N 0000	Graphite	Aluminized glass	189 kA	Layers oriented -45°, +45°, -45°, and +45°, coating damage confined to ½- by 1-in. area, no damage to substrate

Table A-2–Continued

Test serial number	Test panel	Coating	Test discharge	Remarks
477 GP86 A105N 0000	Graphite	Aluminized glass	186 kA	Layers oriented +45° and 45°, coating damage confined to ½ by ½ in. area, minor damage to substrate at contact point
478 BR39 A105N 0000	Boron	Aluminized glass	187 kA	Layers oriented +45° and 45°, coating damage limited to ½ in. dia area, no damage to substrate
479 BR16 A110N 0000	Boron	Aluminized glass	187 kA	Layers oriented +45°, -45°, +45° and -45°, coating damage limited to ½ in. dia area, no damage to substrate
480 BR17 A109N ALCO	Boron	Aluminized glass	200 kA	Layers oriented 0°, 90°, 90° and 0°, coating vaporized in ½-in.-dia area, substrate sustained a crack and other minor damage in the ½-in.-dia area
481 BR18 A109N ALCO	Boron	Aluminized glass	100 kA	Layers oriented 0°, 90°, 90° and 0°, no damage to substrate or coating
482 BR19 A109N ALCO	Boron	Aluminized glass	22 C	Layers oriented 0°, 90°, 90° and 0°, a 94-kA discharge triggered a 22 C discharge at a 55-A dc current for 0.4 sec, about twenty 0.05-in.-dia pock marks on coating, no damage to substrate
483 BR20 A109N ALCO	Boron	Aluminized glass	85 C	Layers oriented 0°, 90°, 90°, and 0°, a 94-kA discharge triggered an 85-C discharge at an 88-A dc current for 0.96 sec, about fifty 0.3-in.-dia pock marks on coating; substrate slightly damaged
484 GP87 A109N ALCO	Graphite	Aluminized glass	200 kA	Layers oriented 0°, 90°, 90° and 0°; discharge made 3/8-in.-dia hole through coating and substrate
485 GP88 A109N ALCO	Graphite	Aluminized glass	103 kA	Layers oriented 0°, 90°, 90°, and 0°, no damage to coating or substrate
466 AL01 00000 0000	80-mil aluminum plate	None	209 C	A 100-kA discharge triggered a 209-C discharge at a 255-A dc current for 0.82 sec; ¾-in.-dia area melted through panel. Panel also tested in undamaged area with a second discharge of 100-kA which triggered a 110-C discharge at a 255-A dc current for 0.43 sec; ½-in.-dia area melted through the panel
487 AL02 00000 0000	80-mil aluminum plate	None	64 C	A 100-kA discharge triggered a 64-C discharge at a 255-A dc current for 0.25 sec. 7/16-in.-dia area melted through panel
488 AL03 00000 0000	80-mil aluminum plate	None	101 C	A 110-kA discharge triggered a 101-C discharge at a 87-A dc current for 1.16 sec; 7/16-in.-dia area melted through panel
489 AL04 00000 0000	80-mil aluminum plate	None	101 C	A 110-kA discharge triggered a 101-C discharge at a 23.3-A dc current for 4.35 sec; discharge made flash mark on surface but did not melt through panel
490 AL05 00000 0000	80-mil aluminum plate	None	98 C	A 110-kA discharge triggered a 98-C discharge at a 392-A dc current for 0.25 sec ½-in.-dia area melted through panel
491 BR21 AR04Z 0000	Boron	Aluminum wire fabric	110 kA	Coating slightly damaged in 1-in.-dia area; no damage to substrate
492 BR22 AR04Z 0000	Boron	Aluminum wire fabric	88 C	A 93 kA discharge triggered an 88-C discharge at a 168-A dc current for 0.52 sec, high-current arc traced random path on 3½- by 4-in. area of coating, no damage to substrate
493 BR23 AW10C 0000	Boron	Metal fibers	85 kA	Discharge removed 60% of coating in a 5-in.-dia area, no damage to substrate

Table A-2—Continued

Test serial number	Test panel	Coating	Test discharge	Remarks
494-BR24-AW20C-0000	Boron	Metal fibers	90 kA	Discharge delaminated coating from substrate at arc attachment point; no damage to substrate
495-GP89-AW10C-0000	Graphite	Metal fibers	85 kA	Some damage to coating, no damage to substrate
496-GP90-AW20C-0000	Graphite	Metal fibers	90 kA	No damage to coating or substrate
497-BR25-AI18N-0000	Boron	Aluminized glass	52 C	Eight layers oriented 0° and 90°; a 91-kA discharge triggered a 52-C discharge at a 137-A dc current for 0.38 sec; 10 pits made in 1- by 2-in. area, the largest 5/16 by 3/16 in.; substrate damaged at some larger pit locations
498-BR26-AR04Z-FG04	Boron	Aluminum wire fabric	197 kA	Coating damaged in 1½-in.-dia cloverleaf pattern, no damage to substrate
499-BR27-AR04Z-FG04	Boron	Aluminum wire fabric	232 C	A 97-kA discharge triggered a 232-C discharge at a 165-A dc current for 1.41 sec; high-current arc wandered over 5- by 7-in. area causing moderate damage to coating; substrate undamaged
500-BR28-AR08X-FG04	Boron	Aluminum wire fabric	197 kA	Coating moderately damaged in 3/8-in.-dia area; no damage to substrate
501-BR29-AR08X-FG04	Boron	Aluminum wire fabric	175 C	A 92-kA discharge triggered a 175-C discharge at a 199-A dc current for 0.88 sec; coating removed from 1½-in.-dia area; substrate damaged in same area
502-GP91-AC03C-0000	Graphite	Acrylic paint	100 kA	8- by 8-in. panel with copper tape along each edge parallel to induced current flow; discharge removed acrylic paint from 1- by 3-in. area; substrate damaged in a 1- by ½-in. area, delaminating outer three layers
503-BR30-AI05N-0000	Boron	Aluminized glass	194 kA	Layers oriented -45° and +45°; discharge severely damaged outer coating layer in 2¼- by 1-5/8-in. area; no damage to substrate
504-BR31-AI05N-0000	Boron	Aluminized glass	319 C	Layers oriented -45° and +45°; an 89-kA discharge triggered a 319-C discharge at a 188-A dc current for 1.70 sec; discharge made 1-in.-dia hole through panel; severe damage to substrate
505-GP92-AI05N-0000	Graphite	Aluminized glass	194 kA	Layers oriented -45° and +45°; coating damaged in 1-7/8- by 1½-in. area and completely removed in ½-in.-dia area, substrate damaged at that point
506-GP93-AI05N-0000	Graphite	Aluminized glass	180 C	Layers oriented -45° and +45°; an 89-kA discharge triggered a 180-C discharge at a 168-A dc current for 1.07 sec; arc wandered over most of panel surface causing moderate damage to coating; no damage to substrate
507-GP94-AR04Z-0000	Graphite	Aluminum wire fabric	214 C	A 92-kA discharge triggered a 214-C discharge at a 202-A dc current for 1.11 sec; discharge destroyed coating in 1¼-in.-dia area, 1-in.-dia crater burned in substrate
508-GP95-AR04Z-0000	Graphite	Aluminum wire fabric	231 C	A 92-kA discharge triggered a 231-C discharge at a 210-A dc current for 1.10 sec; coating destroyed in 1- by 1¼-in. area; 7/8 by 1-1/8-in. crater burned in substrate
509-GP96-AR04Z-0000	Graphite	Aluminum wire fabric	–	Panel used for triboelectric charging and electromagnetic shielding studies
510-GP97-AR08X-0000	Graphite	Aluminum wire fabric	–	Panel used for triboelectric charging and electromagnetic shielding studies
511-GP98-AI05N-0000	Graphite	Aluminized glass	–	Panel used for triboelectric charging and electromagnetic shielding studies
512-BR32-AR04Z-0000	Boron	Aluminum wire fabric	–	Panel used for triboelectric charging and electromagnetic shielding studies
513-BR33-AR08X-0000	Boron	Aluminum wire fabric	–	Panel used for triboelectric charging and electromagnetic shielding studies
514-BR34-AI05N-0000	Boron	Aluminized glass	–	Panel used for triboelectric charging and electromagnetic shielding studies

Table A-2—Concluded

Test serial number	Test panel	Coating	Test discharge	Remarks
515 GP99 00000 ALCO	Graphite	Uncoated	214 C	An 87 kA discharge triggered a 214 C discharge at a 210-A dc current for 1.02 sec. 1¼ in. dia crater burned in graphite, moderate damage over 2½ in. dia area. A second test to 12 by 12 in. sample was directed at an undamaged area, discharge with a peak current of 192 kA severely damaged an area 5 by 2½ in.
516 BR35 00000 ALCO	Boron	Uncoated	196 C	A 74 kA discharge triggered a 196 C discharge at a 185 A dc current for 1.06 sec. panel damage extended over a 3½ by 3 in. area with additional weakening of the panel in ½ in. wide strip from arc attachment point to electrical ground. A second test to 12 by 12 in. sample was directed at an undamaged area, discharge with a peak current of 149 kA made a 3/8 in. dia hole in center of 2 by 2½ in. cross shaped damage area
517 GP00 CZ04Z 0000	Graphite	Bronze wire fabric	96 kA	Discharge damaged coating in 1 1/8 in. dia cloverleaf pattern, no damage to substrate
518 GP01 CZ04Z 0000	Graphite	Bronze wire fabric	200 kA	Discharge damaged coating in 2¼ in. dia cloverleaf pattern, coating completely removed from center of cloverleaf in 1 by 3/8 in. area, substrate damaged at arc attachment point
519 BR36 CZ04Z 0000	Boron	Bronze wire fabric	93 kA	Discharge damaged coating in a 1¾ by 1½ in. cloverleaf pattern [illegible] damage to substrate
520 BR37 CZ04Z 0000	Boron	Bronze wire fabric	189 kA	Discharge damaged coating in a 3 by 2½ in. cloverleaf pattern, substrate damaged in small area at arc attachment point

Table A-3. Mechanical Properties of Unexposed Laminates

Graphite			Boron		
Specimen	Tensile strength (ksi)	Tensile modulus (psi x 10^6)	Specimen	Tensile strength (ksi)	Tensile modulus (psi x 10^6)
Uni[illegible]ectional			Unidirectional 3-inch tape		
1	11[illegible]	16.8			
2	107	18.1	1	161	15.5
3	119	16.9	2	187	18 1
4	127	20.4	3	170	17 4
5	120	18.0	4	193	17 5
6	113	18.1	5	174	17.9
avg	117	18.0	avg	177	17 3
Bidirectional			Unidirectional 2-inch tape		
1	72.5	10.5	1	189	19 7
2	74.0	10.7	2	191	14.8
3	69.8	11.2	3	199	15.9
4	71.8	11.0	4	184	15.1
5	68.2	11.1	5	190	14 4
6	76.1	11.0	6	198	18 1
avg	72.1	10.9	avg	192	16.3
Bidirectional (0, 90, 0, 90, 0) with style 120 glass fabric coating			Bidirectional (0, 90, 0, 0, 90, 0) with style 120 glass fabric coating		
1	80.2		1	105	
2	79.1		2	114	
3	73.5		3	106	
4	79.8		4	103	
5	81.8		5	115	
6	81.5		6	102	
7	83.5		7	110	
8	84.4		8	116	
9	78.4		9	110	
10	76.0		10	110	
11	73.6		11	107	
avg	80.0		avg	108	

Table A-4. Residual Mechanical Properties of Exposed Laminates

Specimen	Tensile strength (ksi)	Tensile modulus (psi x 10^6)	Specimen	Tensile strength (ksi)	Tensile modulus (psi x 10^6)
300-1	32.1	10.0	350-1	56.1	12.7
2	32.7	9.72	-2	52.7	11.0
3	35.0	10.6	-3	53.3	9.52
4*	29.0	9.84	-4	51.4	15.1
5*	34.2	10.0	-5*	21.8	2.63
6	34.3	9.49	-6*	–NT–	–NT–
7	32.6	11.2	-7*	20.7	4.79
8	28.5	9.37	-8	49.6	11.1
9	31.5	11.0	-9	47.3	11.4
10	31.5	10.1	-10	48.9	10.5
11	30.0	11.1			
avg	32.0	10.2	avg	44.6	9.86
301-1	30.8	12.9	373-1	56.8	15.4
2	32.6	6.84	-2	55.8	13.9
3	34.0	9.92	-3	60.3	12.7
4*	19.5	8.89	-4	63.9	14.8
5*	12.4	12.0	-5	70.7	11.6
6*	23.5	9.51	-6	65.2	13.1
7	32.7	10.0	-7	63.6	12.4
8	30.8	9.80	-8*	67.0	16.1
9	30.4	9.72	-9	68.6	12.5
10	32.5	10.7	10	68.5	12.9
11	33.5	9.98	-11	75.0	15.1
avg	29.3	10.2	avg	65.0	13.7
318-1	80.2	14.2	377-1	61.2	13.2
2	83.0	14.3	-2*	21.6	6.86
3	82.1	16.4	-3*	–NT–	–NT–
4	87.9	14.9	-4*	–NT–	–NT–
5*	85.0	14.1	-5*	5.44	3.37
6*	86.2	13.2	-6	50.7	10.4
7	89.5	13.8	-7	68.6	16.1
8	84.0	14.3	-8	66.3	12.9
9	82.3	13.5	-9	64.6	13.5
10	88.0	14.4	-10	63.8	11.5
11	81.1	15.9	11	68.2	14.1
avg	84.5	14.5	avg	52.3	11.3
348-1	52.6	12.2	388-1	39.3	11.8
2	49.0	10.5	2	39.8	13.3
3	57.0	11.0	-3	38.8	9.86
4*	46.7	18.0	-4	41.2	11.6
5*	36.7	14.2	-5	39.3	11.2
6*	44.5	10.2	-6*	40.7	12.9
7*	68.5	17.9	7*	22.6	7.07
8	50.7	8.75	-8*	39.1	13.5
9	55.2	9.95	9	37.4	11.5
10	54.7	9.43	10	38.2	13.0
			11	38.0	13.4
avg	51.6	12.2	avg	37.7	11.8

* [illegible] damage to coating

Table A-4. –Continued

Specimen	Tensile strength (ksi)	Tensile modulus (psi x 10^6)	Specimen	Tensile strength (ksi)	Tensile modulus (psi x 10^6)
369-1	40.9	11.2	439-1	84.0	17.6
-2	41.1	12.8	-2	80.1	15.3
-3*	42.9	13.5	-3	72.5	15.2
-4*	41.6	16.0	-4	75.8	15.5
-5*	39.6	12.3	-5	78.0	14.5
-6*	40.5	12.4	-6	71.6	12.1
-7	39.3	13.6	-7	74.1	17.0
-8	40.5	11.9	-8	78.3	14.3
-9	38.7	11.1	-9	83.8	15.3
-10	38.9	11.6	-10	63.8	11.8
-11	39.7	10.1	-11	78.5	16.1
avg	40.3	12.4	avg	76.4	15.0
426-1	—	—	444-1	68.4	19.4
-2	98.4	23.7	-2	67.4	24.7
-3	84.8	19.9	-3	74.2	19.0
-4*	75.9	27.4	-4*	69.1	18.8
-5*	75.1	22.2	-5*	55.2	23.1
-6*	63.2	16.3	-6*	20.5	7.15
-7*	79.9	18.2	-7*	75.2	21.1
-8	90.4	25.8	-8	68.1	21.6
-9	92.0	19.5	-9	70.6	17.6
-10	82.7	20.4	-10	59.6	16.9
avg	82.5	21.5	avg	62.8	18.9
427-1	83.4	16.3	445-1	70.9	18.9
-2	83.0	16.7	-2	62.0	18.5
-3	81.5	16.6	-3	73.6	18.9
-4	90.6	16.7	-4	77.0	20.0
-5*	83.5	16.3	-5	82.7	21.4
-6*	83.5	16.9	-6*	10.3	1.76
-7	87.2	17.2	-7*	67.9	14.3
-8	79.0	16.7	-8	72.3	25.6
-9	81.6	16.0	-9	72.1	18.4
-10	78.0	16.6	-10	75.0	22.5
-11	88.0	17.3			
avg	83.6	16.7	avg	66.4	18.0
433-1	68.8	20.6	450-1	71.9	16.6
-2	68.6	20.0	-2	77.9	15.9
-3	79.4	16.0	-3	72.6	20.8
-4	79.2	16.5	-4*	78.0	13.1
-5	86.1	16.8	-5*	74.0	14.8
-6*	77.1	17.6	-6*	68.2	14.0
-7	76.0	18.0	-7*	65.1	17.7
-8	76.8	18.1	-8*	69.7	18.7
-9	81.3	16.9	-9*	58.6	16.7
-10	83.6	19.1	-10*	61.1	15.3
			-11	75.8	14.9
avg	77.7	18.0	avg	70.3	16.2

*Visible damage to coating

Table A-4. – Continued

Specimen	Tensile strength (ksi)	Tensile modulus (psi x 10^6)	Specimen	Tensile strength (ksi)	Tensile modulus (psi x 10^6)
452-1	77.8	15.4	457-1	70.5	17.2
-2	73.2	15.3	-2	62.3	16.6
-3	62.0	13.6	-3	81.5	19.1
-4*	58.6	17.4	-4	83.4	15.2
-5*	–NT–	–NT–	-5	87.8	16.0
-6*	–NT–	–NT–	-6*	86.0	14.1
-7*	23.6	5.86	-7*	91.5	18.9
-8	82.8	12.0	-8*	83.6	19.1
-9	75.0	15.0	-9	92.1	18.1
-10	81.6	13.2	-10	92.2	18.3
-11	84.9	16.5	-11	80.9	17.1
avg	68.8	13.8	avg	83.0	17.2
453-1	39.7	15.6	458-1	65.6	19.7
-2	45.0	18.0	-2	80.4	16.9
-3	33.1	16.5	-3	76.0	20.3
-4	44.0	16.2	-4	71.9	16.2
-5	44.7	18.3	-5	83.1	20.8
-6*	18.6	12.2	-6*	55.5	17.8
-7	41.3	19.1	-7	74.8	19.3
-8	39.1	14.2	-8	78.5	26.8
-9	38.3	14.6	-9	78.7	18.1
-10	31.4	13.8	-10	86.5	18.1
-11	22.7	13.9			
avg	36.2	15.7	avg	75.1	19.4
454-1	95.4	20.9	459-1	81.9	20.0
-2	94.9	22.5	-2	78.8	27.5
-3	88.2	20.7	-3	86.4	18.6
-4	87.3	18.4	-4*	31.4	20.5
-5	93.6	22.1	-5*	–NT–	–NT–
-6*	79.3	15.3	-6*	52.7	20.4
-7	101.	18.4	-7	82.6	20.6
-8	89.3	17.3	-8	75.6	19.2
-9	92.6	18.9	-9	81.5	16.6
-10	93.0	18.7	-10	83.1	18.8
-11	88.0	19.8			
avg	91.1	19.4	avg	72.7	20.2
456-1	86.5	18.2	461-1	82.0	18.5
-2	80.9	17.6	-2	73.0	17.6
-3*	43.5	11.6	-3	80.6	20.7
-4	59.9	17.4	-4*	68.6	17.7
-5*	45.5	12.7	-5*	42.0	13.4
-6*	–NT–	–NT–	-6	81.3	21.6
-7*	62.6	14.6	-7	80.8	18.1
-8	69.3	17.4	-8	79.5	20.0
-9	78.2	15.5	-9	79.1	15.6
-10	75.8	17.4	-10	70.4	18.3
-11*	69.9	18.6			
avg	67.2	16.1	avg	73.7	18.1

* [illegible] damage to coating

Table A-4.—Continued

Specimen	Tensile strength (ksi)	Tensile modulus (psi x 10^6)	Specimen	Tensile strength (ksi)	Tensile modulus (psi x 10^6)
472-1	116.	20.4	476-1	54.8	15.8
-2	103.	19.6	-2	51.1	15.7
-3	97.5	19.6	-3	50.1	12.5
-4	105.	20.2	-4	47.6	6.80
-5*	114.	19.8	-5*	40.4	12.8
-6*	105.	15.5	-6	37.4	11.1
-7*	107.	16.6	-7	56.1	12.7
-8*	106.	18.2	-8	50.4	10.8
-9	108.	22.1	-9	44.8	16.0
-10	95.5	20.0	-10	39.8	8.09
-11	97.8				
avg	105.0	19.3	avg	47.3	12.2
473-1	87.9	21.5	477-1	53.3	14.6
-2	89.3	18.8	-2	58.3	9.00
-3	92.2	20.9	-3	64.2	17.9
-4	89.3	18.9	-4	63.0	9.52
-5*	113.	27.1	-5	54.3	9.79
-6*	97.6	21.8	-6*	25.6	11.0
-7*	96.5	21.4	-7	61.3	18.1
-8	97.7	24.2	-8	56.2	11.5
-9	85.7	20.0	-9	56.2	13.8
-10	88.9	19.6	-10	63.4	16.9
avg	93.8	21.4	avg	55.6	13.2
474-1*	105.	19.8	478-1	86.9	15.9
-2*	108.	19.6	-2	82.6	15.8
-3*	103.	20.5	-3	84.4	17.1
-4*	31.6	8.15	-4	87.9	14.6
-5*	–NT–	–NT–	-5	83.3	14.5
-6*	–NT–	–NT–	-6	80.6	14.3
-7*	33.1	2.72	-7	86.0	15.9
-8*	100.	11.6	-8	85.4	16.0
-9*	101.	15.4	-9	77.6	16.7
-10	109.	20.1	-10	86.2	13.7
-11	111.	19.6	-11	79.6	15.8
avg	89.1	15.3	avg	83.7	15.5
475-1	95.6	20.9	479-1	69.2	12.7
-2	112.	22.6	-2	72.5	12.7
-3	88.8	20.6	-3	64.0	13.4
-4	93.7	21.4	-4	65.1	13.2
-5*	95.4	19.1	-5	68.5	13.0
-6*	–NT–	–NT–	-6	62.9	11.2
-7*	37.0	14.4	-7	64.2	12.5
-8	98.4	23.7	-8	72.9	10.4
-9	104.0	21.6	-9	69.2	12.0
-10	96.3	22.1	-10	72.1	13.5
			-11	68.6	12.6
avg	91.2	20.7	avg	68.1	12.5

* Visible damage to coating

Table A-4.—Concluded

Specimen	Tensile strength (ksi)	Tensile modulus (psi x 10^6)	Specimen	Tensile strength (ksi)	Tensile modulus (psi x 10^6)
498-1	91.6	22.4	505-1	55.4	16.7
-2	99.5	19.7	-2	61.2	16.3
-3	91.4	19.7	-3	61.8	17.1
-4	80.3	26.4	-4	59.9	14.6
-5	93.1	23.7	-5	61.5	15.9
-6	92.2	19.6	-6	56.0	15.0
-7	91.7	19.2	-7*	14.2	13.7
-8	96.6	26.9	-8*	49.4	12.9
-9	88.9	23.5	-9	63.0	19.7
-10	99.7	19.9	-10	60.3	18.5
-11	93.7	19.5	-11	60.9	18.9
avg	92.6	21.9	avg	54.9	16.3
499-1	101.	23.2	506-1	61.6	19.0
-2	88.3	19.8	-2	56.1	21.5
-3	97.3	22.0	-3	54.0	24.4
-4*	96.1	16.5	-4	64.4	21.3
-5*	90.9	19.0	-5	61.8	19.4
-6*	94.5	19.1	-6	62.5	17.7
-7	93.5	24.1	-7	64.0	22.6
-8	101.	19.1	-8	57.7	20.6
-9	87.6	21.7	-9	59.4	19.9
-10	94.7	22.9	-10	61.1	22.7
-11	86.7	19.7	-11	61.2	17.4
avg	93.8	20.6	avg	60.3	20.6

*Visible damage to coating

Note: All panels except the following were of 0 , 90 , 0 , 90 , 0 orientation.

a) 0°, 90°, 0°, 0°, 90°, 0°–426, 454, 472, 473, 474, 475, 498, 499

b) 0°, 90°, 0°, 90°, 0°, 90°–373 377, 505, 506

c) 90°, 0°, 90°, 90°, 0°, 90° 300, 301, 388, 389, 453

Table A-5. Residual Mechanical Properties of Boeing-McDonnell Douglas Test Laminates

Specimen	Tensile strength (ksi)	Tensile modulus (psi x 10^6)	Specimen	Tensile strength (ksi)	Tensile modulus (psi x 10^6)
BR5-1	75.8	22.3	BR5C-1	70.0	13.1
-2	79.1	18.4	-2	87.5	17.2
-3	83.0	20.8	-3	77.6	20.0
-4	78.1	17.4	-4	88.6	20.7
-5*	73.5	16.1	-5	81.1	16.3
-6*	74.4	16.3	-6*	70.5	17.3
-7*	69.6	16.3	-7*	39.7	18.8
-8*	61.3	15.4	-8*	16.3	10.6
-9*	73.7	16.4	-9*	34.1	13.0
-10	80.1	18.6	-10*	56.6	22.0
-11	84.5	18.2	-11*	37.3	17.2
-12*	78.9	21.9	-12*	10.7	3.61
-13*	79.6	19.2	-13*	62.3	18.6
-14*	64.1	17.3	-14*	62.3	15.3
-15*	58.6	17.4	-15	82.4	18.1
-16	82.7	18.4	-16	73.2	15.2
-17	72.4	15.8	-17	70.6	17.4
-18	75.7	20.8	-18	72.4	18.3
-19	86.2	22.2	-19	73.1	17.2
-20	79.2	18.1	-20	83.2	19.1
-21	84.0	19.1	-21	86.9	18.7
-22	81.2	18.9	-22	87.7	19.2
GR5-1	65.8	20.9	GR5C-1	60.6	17.3
-2	45.1	20.4	-2	66.3	20.2
-3	64.3	14.7	-3	66.3	22.0
-4	67.8	20.6	-4	63.8	22.8
-5	61.8	18.7	-5	67.3	18.7
-6	61.4	19.7	-6*	65.5	20.5
-7*	62.6	20.8	-7*	58.2	19.4
-8*	60.7	21.4	-8*	37.9	16.4
-9*	59.0	20.0	-9*	59.6	18.0
-10	61.1	21.6	-10	64.2	19.9
-11	60.5	18.2	-11	57.4	21.2
-12	62.8	20.7	-12	63.0	20.4
-13	56.3	18.3	-13	59.8	19.0
-14	62.3	18.9	-14*	58.2	21.7
-15	53.9	20.3	-15*	7.36	2.41
-16	55.6	21.9	-16*	34.8	18.6
-17	61.1	20.9	-17	63.5	22.8
-18	61.1	21.6	-18	64.6	21.8
-19	55.6	23.5	-19	61.7	20.4
-20	54.2	19.1	-20	68.3	22.7
-21	63.9	18.2	-21	63.6	17.5
-22	63.3	18.7	-22	62.5	20.9

*Visible damage to coating or composite

Table A-5.—Concluded

Specimen	Tensile strength (ksi)	Tensile modulus (psi x 10^6)	Specimen	Tensile strength (ksi)	Tensile modulus (psi x 10^6)
BR14-1	57.5	19.0	BR14C-1	90.8	19.6
-2	63.4	15.9	-2	91.6	19.0
-3	77.7	16.2	-3	85.1	20.2
-4	79.8	15.4	-4	96.7	20.9
-5	49.4	16.6	-5*	66.8	15.9
-6*	52.3	12.9	-6*	50.0	16.9
-7*	27.3	15.5	-7*	NT	NT
-8*	NT	NT	-8*	33.2	9.35
-9*	50.9	14.9	-9*	82.4	16.2
-10*	54.6	15.2	-10	96.4	17.4
-11	68.1	16.1	-11*	77.6	16.4
-12	75.3	18.3	-12*	85.3	17.8
-13	59.8	14.0	-13*	65.6	14.7
-14*	41.5	13.0	-14*	12.2	1.97
-15*	5.15	3.69	-15*	25.3	7.67
-16*	46.8	14.2	-16*	64.6	16.6
-17	71.9	15.8	-17	92.2	16.5
-18	85.5	15.3	-18	77.4	18.6
-19	86.5	18.0	-19	89.7	18.5
-20	85.6	18.0	-20	92.5	19.4
-21	84.2	18.2	-21	83.7	17.3
-22	86.6	20.0			
GP14-1	65.4	22.1	GP14C-1	63.9	23.5
-2	71.1	20.6	-2	68.4	17.6
-3	69.2	24.0	-3	66.1	20.4
-4	66.7	20.1	-4	69.9	18.1
-5	64.4	20.2	-5*	68.4	20.2
-6*	66.1	20.9	-6*	62.5	19.4
-7*	38.7	16.7	-7*	20.7	9.75
-8*	35.1	13.6	-8*	24.0	6.21
-9*	66.0	19.3	-9*	37.2	15.3
-10	60.1	16.3	-10*	67.8	21.4
-11	64.0	19.1	-11	66.6	19.8
-12	63.8	17.6	-12	69.0	17.9
-13*	64.2	21.0	-13	68.9	19.6
-14*	43.8	14.6	-14*	63.4	20.0
-15*	42.7	17.1	-15*	35.8	16.6
-16*	62.3	18.7	-16*	43.8	24.9
-17	65.4	21.4	-17*	55.3	19.8
-18	63.5	19.0	-18	63.9	21.6
-19	64.1	21.9	-19	70.2	20.0
-20	63.4	20.2	-20	66.3	17.9
-21	65.6	20.0	-21	68.1	20.9

*Visible damage to coating or composite

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13. ABSTRACT

Coatings and coating systems developed for protecting boron-filament- and graphite-fiber-reinforced plastic composites from structural damage by lightning strikes were investigated and developed. These coatings are 6-mil-thick aluminum foil, 200 by 200 mesh aluminum wire fabric, 120 by 120 mesh aluminum wire fabric, and a coating containing aluminized glass filaments. These coatings all use a continuous-metal member as the protective element (e.g., metal foil, woven wire fabric, or metallized glass filaments). Each of these was found capable of preventing mechanical damage to the composite at the 100-kA test level. Very local and minor damage was frequently, but not always, detected after 200-kA testing. None of the coatings could fully protect the composites from damage due to the high-coulomb component of the artificial lightning stroke.

With but one exception, the coatings investigated were relatively unaffected by normal aircraft environments. Their electrodynamic properties were measured and assessed.

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